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Current Status of Water Quality in Long, Johanna and Josephine Lakes - A Summary Report on the Detailed Evaluation Study of the Long Lake Chain of Lakes Improvement Project

Environmental Research Group, Inc.
St. Paul, MN

Prepared for

Corvallis Environmental Research Lab., OR

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THE CURRENT STATUS OF WATER QUALITY IN LONG, JOHANNA AND JOSEPHINE LAKES - A SUMMARY REPORT ON THE DETAILED EVALUATION STUDY OF THE LONG LAKE CHAIN OF LAKES IMPROVEMENT PROJECT

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16. ABSTRACT

An evaluation of Long Lake, Minnesota was initiated by Ramsey County and Environmental Research Group, Inc. in February 1978 to determine the effectiveness of a demonstration project on lake restoration. The three-year evaluation study included continuous hydrologic monitoring to describe annual water budgets and phosphorus loading for both basins of Long Lake and in-lake water sampling on Long Lake and Lakes Johanna and Josephine to determine the qater quality benefits from the restoration program. This report summarizes the water quality data collected.

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TABLE OF CONTENTS

	Page
INTRODUCTION	1
METHODS AND MATERIALS	6
Description of Study Lakes	6
Field Sampling Methods	6
Water Quality Analyses	10
Hydrologic Budget	10
Total Phosphorus Loadings	12
Sediment Phosphorus Release Experiments	13
Enrichment (Bioassay) Experiments	14
RESULTS AND DISCUSSION	15
Water Quality	15
Long Lake	15
Principal Water Quality Indicators	15
1978	15
1979	17
1980	17
Nutrient Limitation	23
North Basin	23
TN:TP Ratios	23
Soluble Nutrient	23
Alkaline Phosphatase	27
South Basin	27
TN:TP Ratios	27
Soluble Nutrient	27
Alkaline Phosphatase	27
Lake Johanna	31
Principal Water Quality Indicators	32
Nutrient Limitation	32
Lake Josephine	35

Page

Principal Water Quality Indicators. 35
Nutrient Limitation 35

Phytoplankton 41

Long Lake. 41
Lake Johanna 48
Lake Josephine 48

Macrophytes 55

Long Lake. 55
Lake Johanna 59
Lake Josephine 61

Zooplankton 61

Long lake. 61
Lakes Johanna and Josephine. 71

Hydrologic Budget 71

Long Lake. 71

Total Phosphorus Loadings 81

Long Lake. 81

Sediment Phosphorus Release Experiments 84

Enrichment (Bioassay) Experiments 90

SUMMARY. 95

Probable Lake Response to Restoration Measures. 95

Long Lake. 95

North Basin 98
South Basin 100

LITERATURE CITED 103

LIST OF TABLES

		Page
1.	Morphological and watershed data for Long, Johanna and Josephine Lakes.	7
2.	Procedures for chemical and biological water quality analyses performed on water samples from Long Lake project lakes.	11
3.	Summary of geometric mean water quality conditions for Long Lake. Annual averages were calculated over sampling dates during the July through September periods.	32
4.	Summary of geometric mean water quality conditions for Lake Johanna. Annual averages were calculated over sampling dates during the July through September periods.	36
5.	Summary of geometric mean water quality conditions for Lake Josephine. Annual averages were calculated over sampling dates during the July through September periods.	42
6.	Identification and enumeration of zooplankton samples collected from the north basin of Long Lake.	64
7.	Identification and enumeration of zooplankton samples collected from the south basin of Long Lake.	67
8.	Identification and enumeration of zooplankton samples collected from Lake Johanna.	72
9.	Identification and enumeration of zooplankton samples collected from Lake Josephine.	74
10.	Approximate hydrologic budget for Long Lake south basin, 1979 water year (Units are acre-feet).	76
11.	Approximate hydrologic budget for Long Lake north basin, 1979 water year (Units are acre-feet).	77
12.	Approximate hydrologic budget for Long Lake south basin, 1980 water year (Units are acre-feet).	78
13.	Approximate hydrologic budget for Long Lake north basin, 1980 water year (Units are acre-feet).	79
14.	Approximate total phosphorus loadings to Long Lake north basin, 1979 and 1980 water years (Units are kg P)	82
15.	Approximate total phosphorus loadings to Long Lake south basin, 1979 and 1980 water years (Units are kg P)	83

Page

16. Results of Long Lake sediment phosphorus release experiments; ortho-phosphate phosphorus concentrations of water overlying sediments. 85

17. Results of Long Lake sediment phosphorus release experiments; mass of ortho-phosphate phosphorus of water overlying sediments. 86

18. Results of Long Lake enrichment (bioassay) experiments. Response of cultures to enrichments are expressed as percentages of the control culture after the indicated period of incubation. 91

19. Summary of geometric mean summer water quality conditions for Long Lake tributaries. Annual averages were calculated over sampling dates during the July through September period. 99

LIST OF FIGURES

		Page
1.	Rice Creek Watershed District. District boundaries are roughly coincident with topographic boundaries.	2
2.	Long Lake project sampling stations	9
3.	Long Lake epilimnetic (0-2 meters) total phosphorus concentrations.	16
4.	Long Lake epilimnetic (0-2 meters) chlorophyll a concentrations	16
5.	Long Lake Secchi disc transparencies.	18
6.	Inverse Secchi disc transparencies versus chlorophyll a concentrations for the north basin of Long Lake	21
7.	Inverse Secchi disc transparencies versus chlorophyll a concentrations for the south basin of Long Lake	22
8.	Epilimnetic (0-2 meters) total nitrogen levels in the north basin of Long Lake.	24
9.	Total nitrogen to total phosphorus ratios in the north basin of Long Lake.	24
10.	Epilimnetic (0-2 meters) total soluble inorganic nitrogen in the north basin of Long Lake.	25
11.	Epilimnetic (0-2 meters) ortho-phosphate phosphorus levels in the north basin of Long Lake.	26
12.	Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of the north basin of Long Lake.	26
13.	Epilimnetic (0-2 meters) total nitrogen concentrations in the south basin of Long Lake.	28
14.	Total nitrogen to total phosphorus ratios in the epilimnetic (0-2 meters) waters of the south basin of Long Lake	28
15.	Epilimnetic (0-2 meters) concentrations of total soluble inorganic nitrogen in the south basin of Long Lake.	29
16.	Epilimnetic (0-2 meters) concentrations of ortho-phosphate phosphorus in the south basin of Long Lake.	30

Page

17. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of the south basin of Long Lake. 30

18. Lake Johanna epilimnetic (0-2 meters) concentrations of total phosphorus. 33

19. Lake Johanna epilimnetic (0-2 meters) chlorophyll a concentrations. 33

20. Epilimnetic (0-2 meters) ortho-phosphate phosphorus concentrations in Lake Johanna. 34

21. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of Lake Johanna. 34

22. Lake Johanna epilimnetic (0-2 meters) concentrations of total nitrogen. 37

23. Total nitrogen to total phosphorus ratios in Lake Johanna . . . 37

24. Epilimnetic (0-2 meters) total soluble inorganic nitrogen in Lake Johanna. 38

25. Lake Josephine epilimnetic (0-2 meters) total phosphorus concentrations. 39

26. Lake Josephine epilimnetic (0-2 meters) concentrations of chlorophyll a 39

27. Epilimnetic (0-2 meters) ortho-phosphate phosphorus concentrations in Lake Josephine. 40

28. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of Lake Josephine. 40

29. Lake Josephine epilimnetic (0-2 meters) total nitrogen concentrations. 43

30. Total nitrogen to total phosphorus ratios in Lake Josephine . . 43

31. Lake Josephine epilimnetic (0-2 meters) concentrations of total soluble inorganic nitrogen. 44

32. Occurrence and abundance of major phytoplankton taxa in the south basin of Long Lake. 45

33. Occurrence and abundance of major phytoplankton taxa in the north basin of Long Lake. 49

34. Occurrence and abundance of major phytoplankton taxa in Lake Johanna. 52

Page

35. Occurrence and abundance of major phytoplankton taxa in Lake Josephine. 56

36. Aquatic macrophyte distribution in Long Lake. 60

37. Aquatic macrophyte distribution in Lake Johanna 62

38. Aquatic macrophyte distribution in Lake Josephine 63

39. Anaerobic phosphorus release from the sediment of the north basin of Long Lake. 87

40. Anaerobic phosphorus release from the sediment of the south basin of Long Lake. 88

41. Growth of north basin Long Lake phytoplankton in response to various nutrient additions. 92

42. Growth of south basin Long Lake phytoplankton in response to various nutrient additions. 93

43. Chlorophyll/phosphorus relationship for Long lake and Lakes Johanna and Josephine 97

INTRODUCTION

An evaluation of Long Lake, Minnesota was initiated by Ramsey County and Environmental Research Group, Inc. in February, 1978 to determine the effectiveness of a demonstration lake restoration project awarded to the Rice Creek Watershed District. The three-year evaluation study included continuous hydrologic monitoring to describe annual water budgets and phosphorus loading for both basins of Long Lake and in-lake water sampling on Long Lake and Lakes Johanna and Josephine to determine the water quality benefits from the restoration program.

Long Lake is a 73.1 ha lake located in the northern Twin Cities suburb of New Brighton (mid-lake coordinates T30 N45^{o} 4' 10", R 23W 93^{o} 12' 16"). Primary shoreline land uses on the lake are residential on the north and west and beach and open space on the south and east. Johanna and Josephine are the major lakes in the sourthern watershed of Long Lake, shown in Figure 1.

Rice Creek originates in Clear Lake and meanders southwestward through a chain of lakes to the Mississippi River at Fridley, Minnesota. Long Lake is the lower-most lake in the Rice Creek chain of lakes. Long Lake has two distinct basins with a narrow constriction between basins. The northern basin is heavily influenced by the flow of Rice Creek from the northeast portion of the watershed, while the southern basin receives flow from the southern portion of the watershed. The land drained by Rice Creek upstream of Long Lake is primarily agricultural or open space. Urbanized areas in the northern watershed are limited to the downstream end near its western

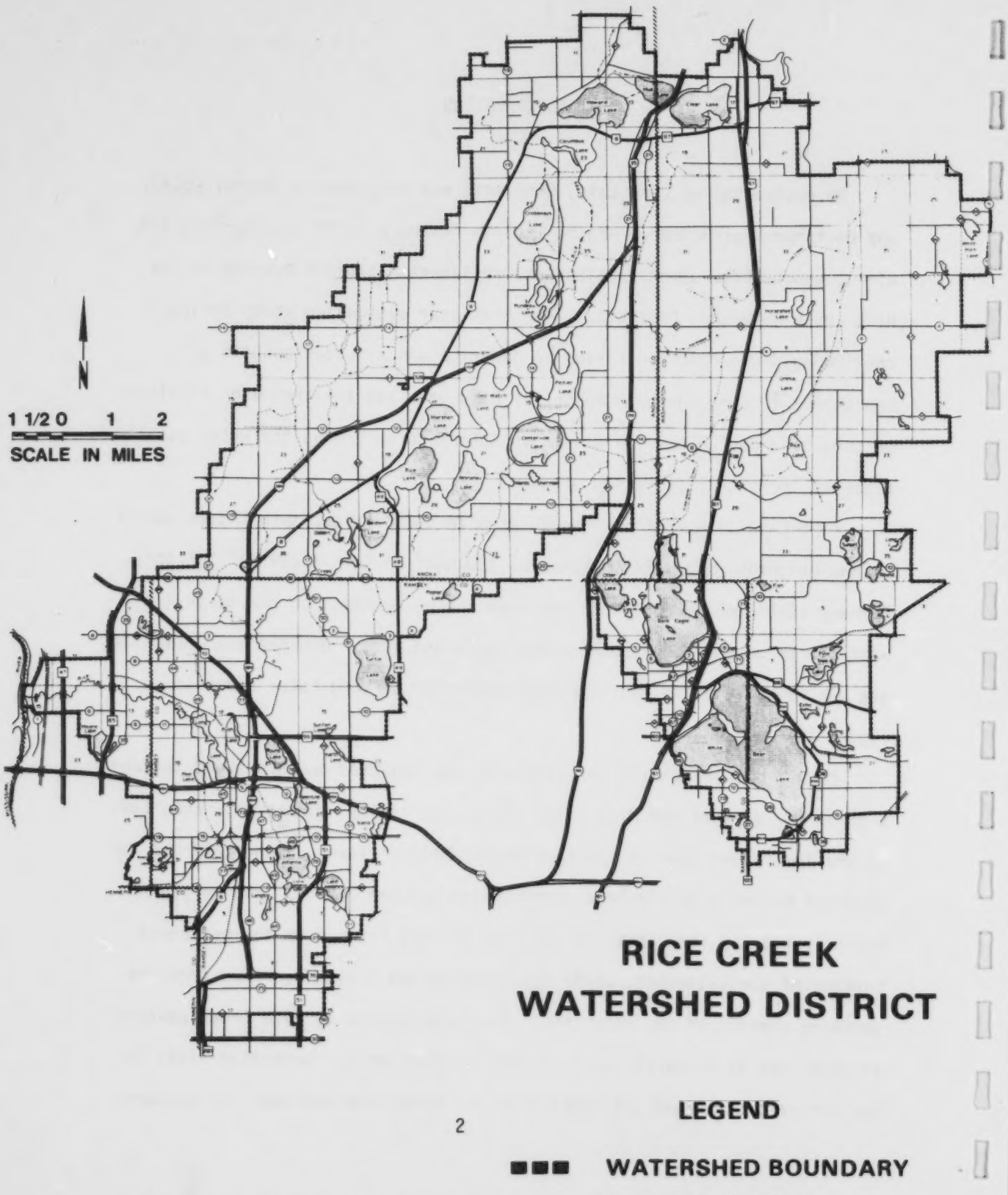


Figure 1. Rice Creek Watershed District. District boundaries are roughly coincident with topographic boundaries.

and southern edges. Suburban expansion of industrial and commercial land uses and residential housing developments are gradually changing the land use of the northern watershed. The southern watershed of Long Lake drains portions of the northern suburbs of St. Paul. A four-lane freeway (I-694) passes to the south of Long Lake and contributes drainage to the south basin. Several lakes within the southern watershed also drain to the south basin of Long Lake, including Josephine and Johanna. An open ditch system connects many of the lakes in the southern watershed. There is little, if any, influence by Rice Creek on the southern basin of Long Lake. The direction of flow within the lake is from the south to the north basin.

As the focal point of the Rice Creek watershed, Long Lake is impacted by both rural nonpoint pollution, primarily sediments, via Rice Creek and urban runoff from the southern watershed. The degradative nature of these inputs is reflected in the chronically poor water quality of Long Lake documented in Ramsey County Water Quality Surveys (1972-1977). The adverse impact of urban runoff extends to other lakes in the southern watershed of Long Lake as well. The increase of impervious surface area with urban development, the loss of natural wetlands and the modification of natural drainageways into open channels or sewer systems has increased both the volume and rate of runoff during storm events in the southern watershed and resulted in higher stormwater loads of nutrients and sediment into many of the lakes. The response of lake levels to storm events in the southern watershed is often rapid and occasional flooding of lakeshore homes can be expected, particularly on Lake Johanna. Inadequate storm sewer capacity results in potential flooding conditions along some drainageways in the southern watershed. Creek bed erosion was particularly severe along parts of the drainage system and contributed substantial sediment loads to down-

stream lakes during periods of high flow. These conditions indicated a need for a watershed approach to the Long Lake Restoration Project.

The Rice Creek Watershed District received a three-year Long Lake Project Grant from the Environmental Protection Agency for 50% of the total project cost of 2.5 million dollars beginning February, 1977. The project goals of the wtershed district and the project consultant, Hickok and Associates of Wayzata, Minnesota, were: a reduction in sediment load from Rice Creek and possible dredging of accummulated sediments; the utilization of wetlands to treat stormwater runoff before it reaches the lakes; upstream improvements intended to reduce sediment transport by the drainage system to Lakes Johanna, Josephine, Little Josephine, Valentine, and Long; reduction of the amount of floodwater; limiting the rise of lake levels during storm events; and reduction of nutrient loads to Long and Josephine Lakes.

Implementation of the upstream improvement projects began in May 1979 and was largely complete by the end of that year. A berm was constructed at the outlet of a wetland south of Long Lake to increase the storage capacity and filtration time of the wetland during periods of overflow from Lake Johanna. A new outlet structure was installed on Lake Johanna to increase discharge capacity during storm events. Streambank stabilization using rock gabions or grouted riprap was done on drainageways tributary to Little Johanna, Valentine and Pike Lakes. Stormwater was diverted from Josephine into marsh-like Little Josephine and an outlet weir was constructed on Little Josephine to increase the water storage capacity of the lake and permit controlled release of water to Lake Josephine.

Additional restoration projects implemented to date include the construction of a four-acre sedimentation basin on Rice Creek upstream of Long Lake in the early spring of 1981 and cosmetic dredging of the lagoon off

the north basin of Long Lake and the deltas formed at the outlets of ditches 2 and 4 into Long Lake.

The Rice Creek Watershed District has received an extension of the Long Lake project period to January 31, 1983. Future plans for the project include modification of an existing wetland into a two-stage system to improve stormwater treatment efficiency, construction of an outlet control structure on Jones Lake to increase water storage capacity and possible application of calcium nitrate to the sediments of a large portion of the south basin of Long Lake to bind phosphorus.

Delays in the implementation of restoration projects on Long Lake have greatly altered the scope of the evaluation study and this report. By the project end date for the evaluation study only the upstream improvements had been completed. Consequently this report cannot evaluate the effectiveness of the Long Lake Restoration Project. The purpose of this report is to summarize the water quality data collected to date.

METHODS AND MATERIALS

Description of Study Lakes

This study was designed to be a multi-year, multi-lake evaluation of changes in water quality parameters resulting from lake restoration activities. Long, Johanna and Josephine Lakes were studied. Table 1 summarizes morphological and watershed information for the study lakes. A high percentage of the land use for each lake is urban and residential. The principal water quality problem in all the lakes is the resulting high volume and deteriorated water quality of stormwater runoff. The watershed of the north basin of Long Lake is less urbanized than that of the south basin, but receives runoff from agricultural land and open space via Rice Creek.

Field Sampling Methods

The plan of research was to sample each of the lakes intensively at a central location, generally at its deepest point. Those points were located in areas that best represented the limnologic properties of the lakes. Two additional sampling sites were monitored on each basin of Long Lake where lake basin morphometry had created different hydrologic and/or limnologic subbasins. One additional sampling site was monitored on Johanna and Josephine Lakes. On each sampling trip, a 2.0 meter epilimnetic composite sample was collected at each sampling station and analyzed for total and soluble phosphorus; nitrite, nitrate, ammonia and total Kjeldahl nitrogen; pH and alkalinity.

Table 1. Morphological and watershed data for Long, Johanna and Josephine Lakes.

Lake	Surface Area (hectares)	Maximum Depth (m)	Mean Depth (m)	Volume (m^3)	Watershed Area (sq km)	Land Use	%
Long	73.1	7.6	4.1	2.98×10^6	111.4	Water	8%
						Marsh	1%
						Forest	4%
(North Basin)	(24.7)	(7.6)	(2.4)	(5.96×10^5)		Cultivated	2%
						Residential	33%
(South Basin)	(48.5)	(7.6)	(5.0)	(2.38×10^6)		Urban	32%
						Pasture/Open	19%
Johanna	86.1	12.2	5.3	4.49×10^6	15.5	Water	6%
						Forest	2%
						Residential	44%
						Urban	39%
						Pasture/Open	8%
Josephine	43.8	13.4	3.6	1.56×10^6	5.2	Water	4%
						Residential	60%
						Urban	32%
						Pasture/Open	4%

Water temperature, dissolved oxygen concentration and specific electrical conductivity were measured along profiles at one-meter intervals at each sampling site. Secchi disc transparency was also measured at each site. Quantitative samples of phytoplankton were taken from the epilimnetic composite samples at the center station for chlorophyll content and identification and enumeration. The sampling periodicity was approximately biweekly during the summer season of active biological growth and approximately monthly during the other seasons.

Phytoplankton from surface water samples were collected for analysis of alkaline phosphatase enzyme activity. Samples for that purpose were obtained from just beneath the surface at the center (deep) sampling station of each lake.

During summer sampling trips, zooplankton samples were collected from the study lakes. A vertical tow with a Wisconsin-style plankton net was made from the bottom to the surface of each lake at its center station. Zooplankton organisms contained in such samples were identified and enumerated and abundance was reported on an areal basis.

Water samples were collected from the inlet and outlet of Rice Creek in the north basin of Long Lake. Samples were also collected from tributaries to the south basin of Long Lake including Johanna Ditch Inlet and Pike Lake Outlet. These samples were subjected to analyses for total and soluble phosphorus; nitrite, nitrate, ammonia and total Kjeldahl nitrogen; and total suspended solids and volatile suspended solids. Lake and stream sampling stations are shown in Figure 2.

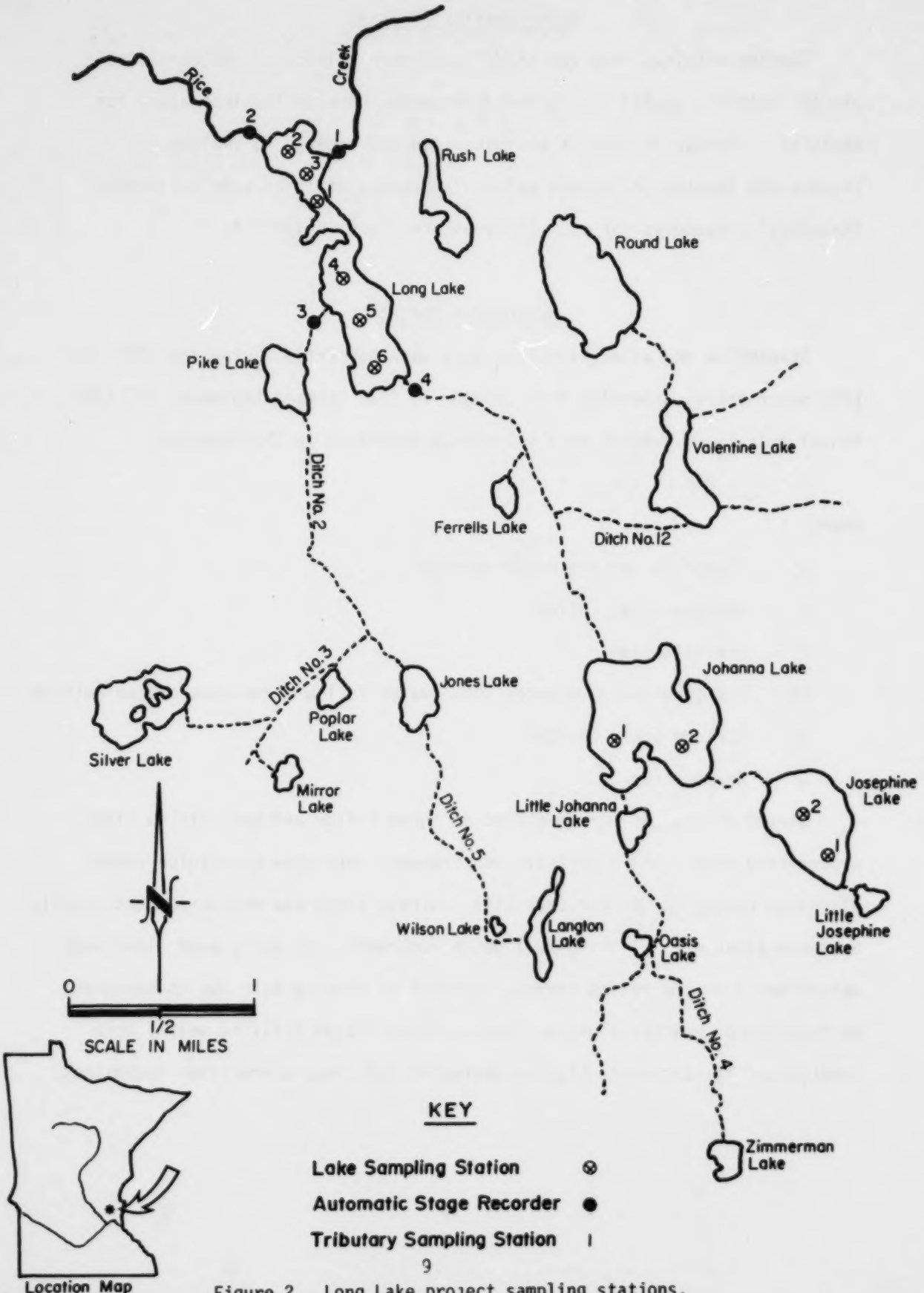


Figure 2. Long Lake project sampling stations.

Water Quality Analyses

Samples obtained from the study lakes were collected into one-liter plastic bottles, packed in ice and transported back to the laboratory for analysis. Storage of samples was minimized and limited to maximum recommended lengths of storage before laboratory analyses were performed. Analytical procedures for such analyses are given in Table 2.

Hydrologic Budget

Streamflow and water resources data were collected during the 1979 and 1980 water years, extending from October 1, 1978 through September 30, 1980. Annual hydrologic budgets were calculated according to the equation:

$$S = S_I + P \pm GW - S_O - E$$

where:

S = Change in surface water storage

S_I = Surface water inflow

P = Precipitation

GW = Net groundwater change, groundwater inflow minus groundwater outflow

S_O = Surface water outflow

E = Evaporation

Stream discharges were measured at three inflow and one outflow sites around Long Lake. These periodic measurements were used to develop stage-discharge rating curves for each site. Stream stage was monitored continuously at those sites with stilling-well depth recorders, and daily mean flows were determined from the rating curves. Periods of missing data due to equipment malfunction or weather problems (particularly frozen stilling wells) were synthesized by station-to-station averaging and cross-correlation techniques.

Table 2. Procedures for chemical and biological water quality analyses performed on water samples from Long Lake project lakes.

Analysis	Procedure (Year of Study)	Reference
Total Phosphorus	Standard Methods (1978) EPA Methods (1979-1980)	APHA, et al., 1975 U.S.-EPA, 1979
Ortho-phosphate Phosphorus	Strickland & Parsons (Murphy-Riley Technique; 1978) EPA Methods (1979-1980)	Strickland & Parsons, 1968 U.S.-EPA, 1979
Nitrite + Nitrate Nitrogen	Strickland & Parsons (Cadmium-Reduction Method; 1978) EPA Methods (1979-1980)	Strickland & Parsons, 1968 U.S.-EPA, 1979
Ammonia Nitrogen	Standard Methods (Indophenol; 1978) EPA Methods (1979-1980)	APHA, et al., 1975 U.S.-EPA, 1979
Total Kjeldahl Nitrogen	EPA Methods	U.S.-EPA, 1976; 1979
Total Hardness	Standard Methods (Titrimetric Methods)	APHA, et al., 1975
Total Alkalinity	Standard Methods (Titrimetric Methods)	APHA, et al., 1975
pH	Standard Methods (Glass Electrode)	APHA, et al., 1975
Dissolved Oxygen	Standard Methods (Winkler Method with Azide Modification)	APHA, et al., 1975
Chlorophyll *a*	Standard Methods (Trichromatic Method)	APHA, et al., 1975
Phytoplankton identification and enumeration	Standard Methods (Sedgewick-Rafter Cell)	APHA, et al., 1975
Zooplankton identification and enumeration	Microscopic Analysis	Ward, J., 1955
Alkaline Phosphatase	p, nitrophenyl phosphate	Berman, T., 1970

Daily precipitation and pan evaporation data were obtained from records at the University of Minnesota - St. Paul Campus weather station. That station is approximately six miles south of Long Lake. Pan evaporation data were multiplied by 0.745, a coefficient recommended by the U.S. Weather Service to convert pan evaporation to lake evaporation in this area.

Change in volume of Long Lake was calculated from biweekly measurements of lake stage and from stage-volume hypsographs. The hypsographs were developed from the bathymetric map produced by the Minnesota Department of Natural Resources. For interpolation purposes, the hypsographs were modeled statistically using quadratic equations.

Net changes in groundwater flow were calculated as the residual to balance the hydrologic budget equation. This residual includes all errors in estimation of the other budget components. Since it contains the summation of errors in the other components it is approximate.

Total Phosphorus Loadings

Phosphorus loadings were calculated for Long Lake on the basis of computed flows and grab samples subjected to water quality analyses. Loadings were calculated as the product of phosphorus concentration in the grab sample and the corresponding flow rate. Loadings for intervening dates were calculated by linear interpolation between water quality sampling dates.

Total phosphorus loads to the north and south basins of Long Lake were estimated by adding groundwater inflow and atmospheric fallout contributions to surface water inflows. It was assumed that the phosphorus concentration of shallow groundwater is 0.02 mg/l (MPCA, 1980), and that atmospheric contributions (precipitation and dry fallout) totalled 0.56 kg/ha (0.5 lbs/acre) of lake surface annually (Murphy and Doskey, 1975; Met. Council, 1981).

It was also assumed that the total phosphorus concentration of south basin waters flowing into the north basin of Long Lake was 0.07 mg/l for loading calculations.

Sediment Phosphorus Release Experiments

An investigation was made into the rates of phosphorus release from the sediments of the north and south basins of Long Lake. Both anaerobic and aerobic rates were determined using a microcosm approach.

Sediment samples from the center stations of the north and south basins of Long Lake were collected using an Ekman dredge. The sediments were placed in clear PVC tubes of 10 cm diameter. Approximately 15 cm of sediment was overlayed by three liters of lake water in the 90 cm tall microcosm and capped with a 5 cm mineral oil seal. Two microcosms were prepared with sediment from each lake basin.

One microcosm from each lake basin was maintained anaerobic by sparging with a slow stream of nitrogen gas bubbles through a glass tube at a distance of 10.0 cm above the sediment layer. The stream of bubbles also served to keep the water layer mixed without suspending sediment particles. Similarly, the remaining two microcosms were kept in an aerobic state by sparging with compressed air.

The microcosms were incubated in a darkened chamber at $20^{o}C$ for a period of 20 days. Small water samples were extracted daily from each microcosm through a sampling port at mid depth in the water column. The concentration of ortho-phosphate phosphorus in each sample was analyzed and plotted against days of incubation to determine sediment phosphorus release rates.

Enrichment (Bioassay) Experiments

Samples of Long Lake phytoplankton were spiked with various nutrients and combinations of nutrients to determine growth-limiting factors. Epilimnetic composite samples from the center sampling stations of the north and south basins of Long Lake were collected and each split into 21, 100 ml aliquots in 300 ml Erlenmayer flasks. The first three flasks of each set were reserved as experimental controls and no additions were made to those samples. Successive triplicate flasks from each set were spiked with 50 µg/l PO_4-P; 300 µg/l NO_3/NH_3-N; PO_4-P and NO_3/NH_3-N; 2 mg/l SiO_2; 1 ml trace metal solution; and lastly, all of the preceeding (P + N + Si + trace metals). The trace metals solution used was made according to the recipe stated in the U.S.-EPA Algal Assay Procedure, Bottle Test. One departure from that recipe was made - EDTA was deleted from the list of ingredients.

The relative fluorescence of each culture was measured in a Turner Model 111 Fluorometer using a 1-cm diameter cell and a suitable scale. The flasks were stoppered loosely with cotton plugs wrapped in cheesecloth and incubated at 20°C and 200 foot-candles of light under a fluorescent ("Cool-White") tube. The cultures were swirled daily and returned to the incubator. Every three or four days the fluorescence of an aliquot from each flask was measured. Each experiment was conducted for a period of about 15 days. Relative fluorescence of samples was plotted against time to determine the growth-limiting factor for each experiment. Enrichment experiments were conducted each year of the study using samples from the north and south basins of Long Lake collected during the June - September periods. Samples for enrichment experiments were collected at the same time routine sampling for nutrients, algal and chlorophyll data was made in order to provide additional information to help in the interpretation of results.

RESULTS AND DISCUSSION

Water Quality

Long Lake

Principal Water Quality Indicators

1978

The Long Lake total phosphorus data exhibit an annual cycle. Elevated concentrations of phosphorus were encountered each summer period in both lake basins. The magnitude of the summer rise in total phosphorus concentrations seems to be related to climatic factors, particularly summer rainfall amounts.

Total phosphorus concentrations in the north basin of Long Lake rose from 0.106 mg/l on 15 June to a maximum of 0.341 mg/l on 25 September 1978. Concentrations declined from that latter date through the winter months into 1979 (Figure 3). A similar pattern was observed in total phosphorus levels in the south basin. Concentrations were lower, however. Maximum total phosphorus concentration was 0.122 mg/l on 27 July, declining through the fall and winter.

Chlorophyll *a* concentrations (Figure 4) exhibited a pattern directly correlated with that of total phosphorus levels during 1978. Levels of chlorophyll were similar in both basins despite dissimilar total phosphorus concentrations. Peak north basin chlorophyll concentration was less than the corresponding south basin level during 1978. The former was 0.075 mg/l on 6 September, while the latter was 0.143 mg/l on the same date.

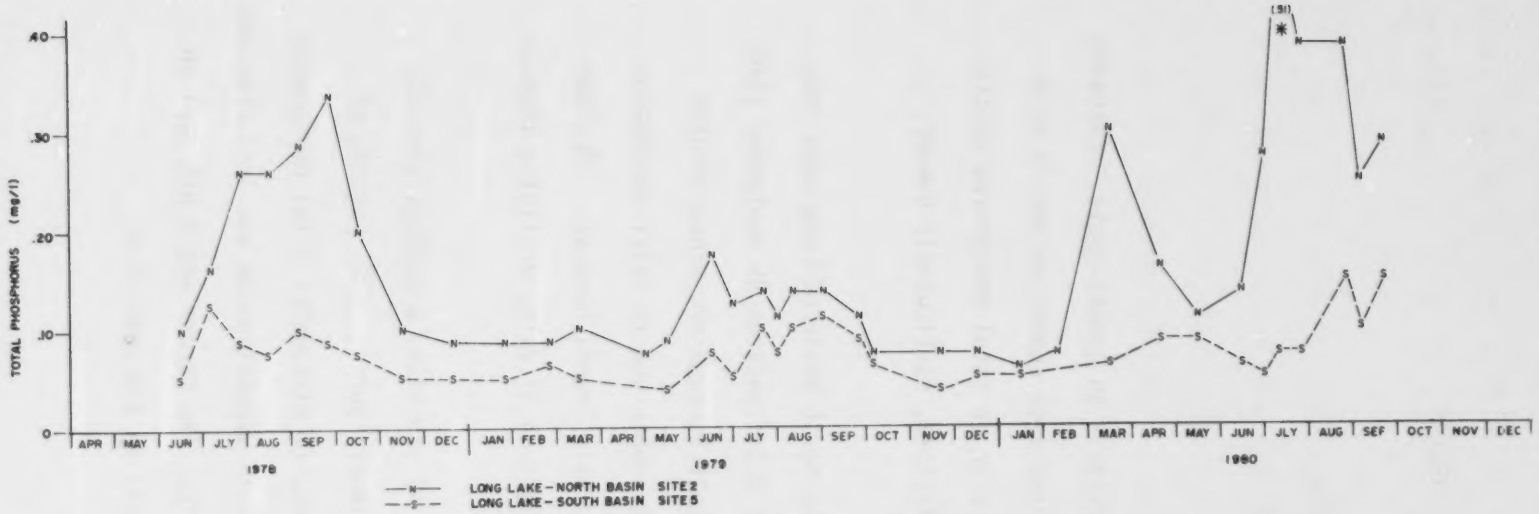

TOTAL PHOSPHORUS (mg/l)
.40
.30
.20
.10
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
(51)
LONG LAKE-NORTH BASIN SITE 2
LONG LAKE-SOUTH BASIN SITE 5

Figure 3. Long Lake epilimnetic (0-2 meter) total phosphorus concentrations.

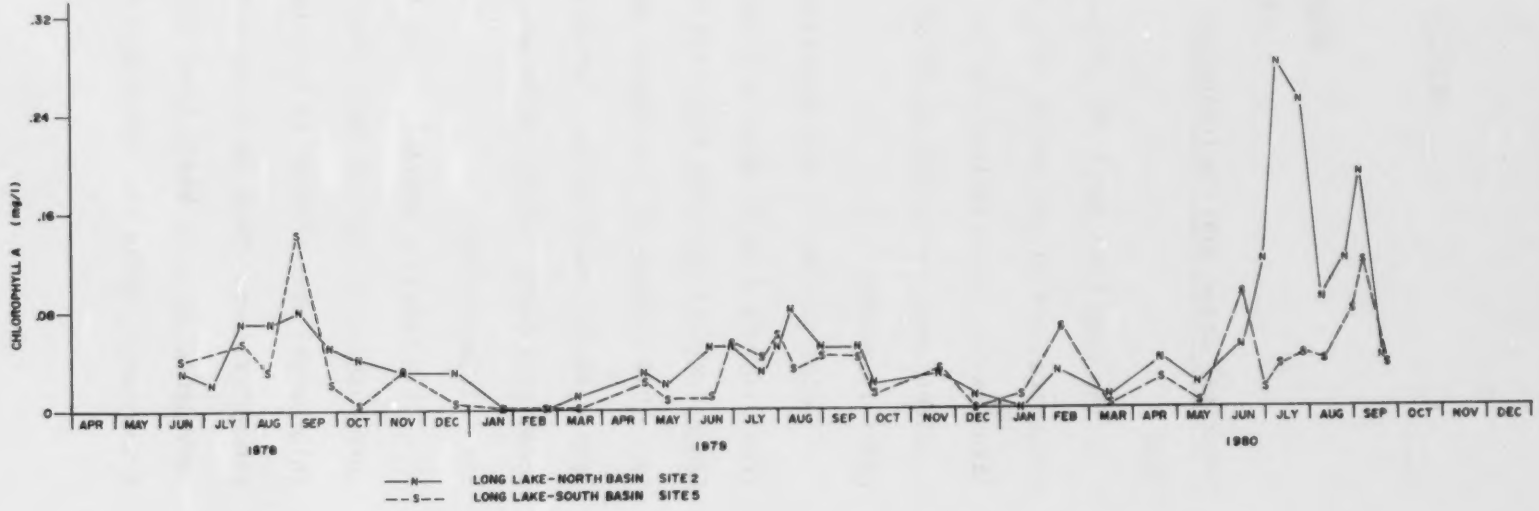

CHLOROPHYLL A (mg/l)
.32
.24
.16
.08
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE-NORTH BASIN SITE 2
LONG LAKE-SOUTH BASIN SITE 5

Figure 4. Long Lake epilimnetic (0-2 meter) chlorophyll a concentrations.

Secchi disc transparencies (Figure 5) paralleled 1978 total phosphorus and chlorophyll a concentrations inversely. Minimum transparencies were coincident with maximum chlorophyll a levels on 6 September. North and south basin transparencies were 0.8 and 0.6 meters, respectively. The large disparity in phosphorus concentrations between lake basins is not reflected in chlorophyll or Secchi disc data, suggesting that light penetration may be restricted in the north basin. This issue is discussed later in this section.

1979

During 1979, total phosphorus concentrations in the north basin of Long Lake were reduced from 1978 levels. A similar annual pattern was observed however. North basin phosphorus reductions were substantial while south basin reductions were only slight. Peak north basin phosphorus concentration, 0.169 mg/l, occurred on 18 June. The corresponding peak in the south basin was 0.078 mg/l on the same date. North basin concentrations of total phosphorus were consistently higher than south basin levels throughout 1979. The differences between 1978 and 1979 phosphorus concentrations seem to be related to summer precipitation totals. This issue is also discussed later in this section.

Chlorophyll a concentrations in 1979 were only slightly lower than 1978 levels for both basins of Long Lake. Peak levels of chlorophyll for the north and south basins were 0.084 mg/l on 13 August and 0.061 mg/l on 2 August, respectively. Minimum Secchi disc transparencies were coincident with those chlorophyll data and were 0.6 and 0.8 meters.

1980

During 1980, total phosphorus concentration in the north basin of Long Lake rose to a maximum concentration of 0.61 mg/l on 13 July. Elevated

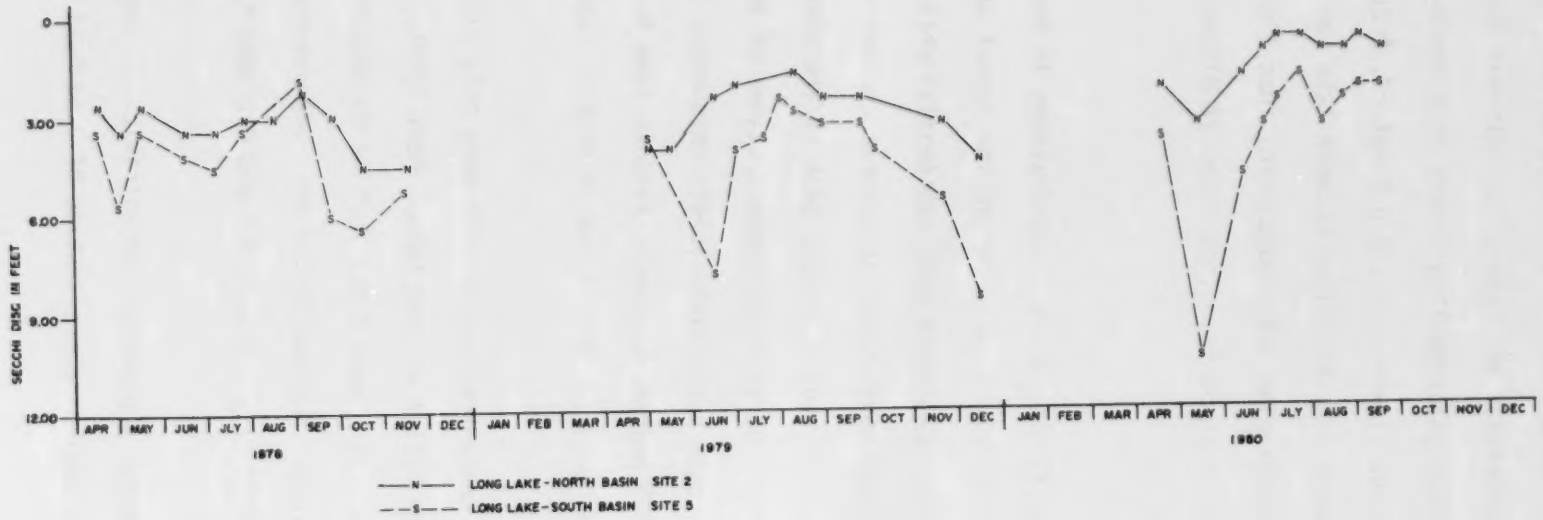

SECCHI DISC IN FEET
0
3.00
6.00
9.00
12.00
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
N LONG LAKE-NORTH BASIN SITE 2
S LONG LAKE-SOUTH BASIN SITE 5

Figure 5. Long Lake Secchi disc transparencies.

levels throughout the summer of 1980 appear to be related to stormwater runoff. South basin concentrations rose only slightly to a maximum of 0.155 mg/l on 22 September.

Chlorophyll a concentrations were more responsive to changes in total phosphorus levels during 1980 than during previous years. This was especially true for the north basin, but evident also in south basin data. Maximum chlorophyll levels were 0.276 mg/l and 0.120 mg/l for the north and south basins on 13 July and 8 September, respectively. Minimum transparencies were observed on the same date, 13 July, for the north basin, but on a different date, 28 July, for the south basin. North and south basin transparencies were 0.2 and 0.6 meters. The corresponding south basin chlorophyll level was 0.046 mg/l.

Large differences in total phosphorus concentrations were observed between the years of study in the north basin of Long Lake. Phosphorus levels in the summers of 1978 and 1980 were significantly higher than in 1979. The difference appears to be related to the precipitation totals during the summer months, July through September. Relatively wet years were encountered in 1978 and 1980, while 1979 was a significantly drier year. The precipitation totals for these summer months were 13.34, 12.11, and 12.77 inches. These totals to not appear exceedingly disparate initially but their distribution over the summer is considerably different.

Rainfall distribution during the summer months of 1978 and 1980 was relatively uniform. The 1978 total, July through September, was distributed 5.91, 5.03 and 2.40 inches, and the 1980 distribution was 3.07, 5.57, and 4.13 inches monthly. Precipitation in the summer of 1979 was 2.09, 7.64, and 2.38 inches, however. Further, the July through mid-August total was only 4.00 inches. The dry weather and subsequently lower phosphorus loadings

to the lake in 1979 apparently resulted in lower in-lake total phosphorus concentrations. The fact that the south basin does not strongly show the year to year fluctuation in total phosphorus concentrations, seem to be related to the presence of the large marsh area between Johanna Lake and the south basin of Long Lake through which the bulk of runoff reaching the south basin via Johanna Creek from the southern watershed must flow. That marsh area appears to buffer the effects of increased runoff, probably through nutrient uptake by marsh plants. Average annual flow from the southern watershed to the south basin (ca. 8000 acre-feet) is significantly lower than that to the north basin (ca. 46,000 acre-feet), and the corresponding phosphorus load is similarly lower. The lower hydraulic and nutrient loads distributed over a larger surface area in the south basin also serve to mitigate concentration fluctuations observed in the smaller, and more heavily loaded, north basin.

Light penetration in the north basin of Long Lake seems to limit phytoplankton growth somewhat. The waters of the north basin are visibly colored. An indication of the water color may be found in a plot of the inverse of Secchi disc transparency against chlorophyll a levels. Plots of such data from the north and south basins of Long Lake are shown in Figures 6 and 7, respectively. The corresponding zero-chlorophyll Secchi disc transparencies are 1.26 and 1.74 meters. The lower transparency calculated for the north basin of Long Lake is indicative of its more highly colored water.

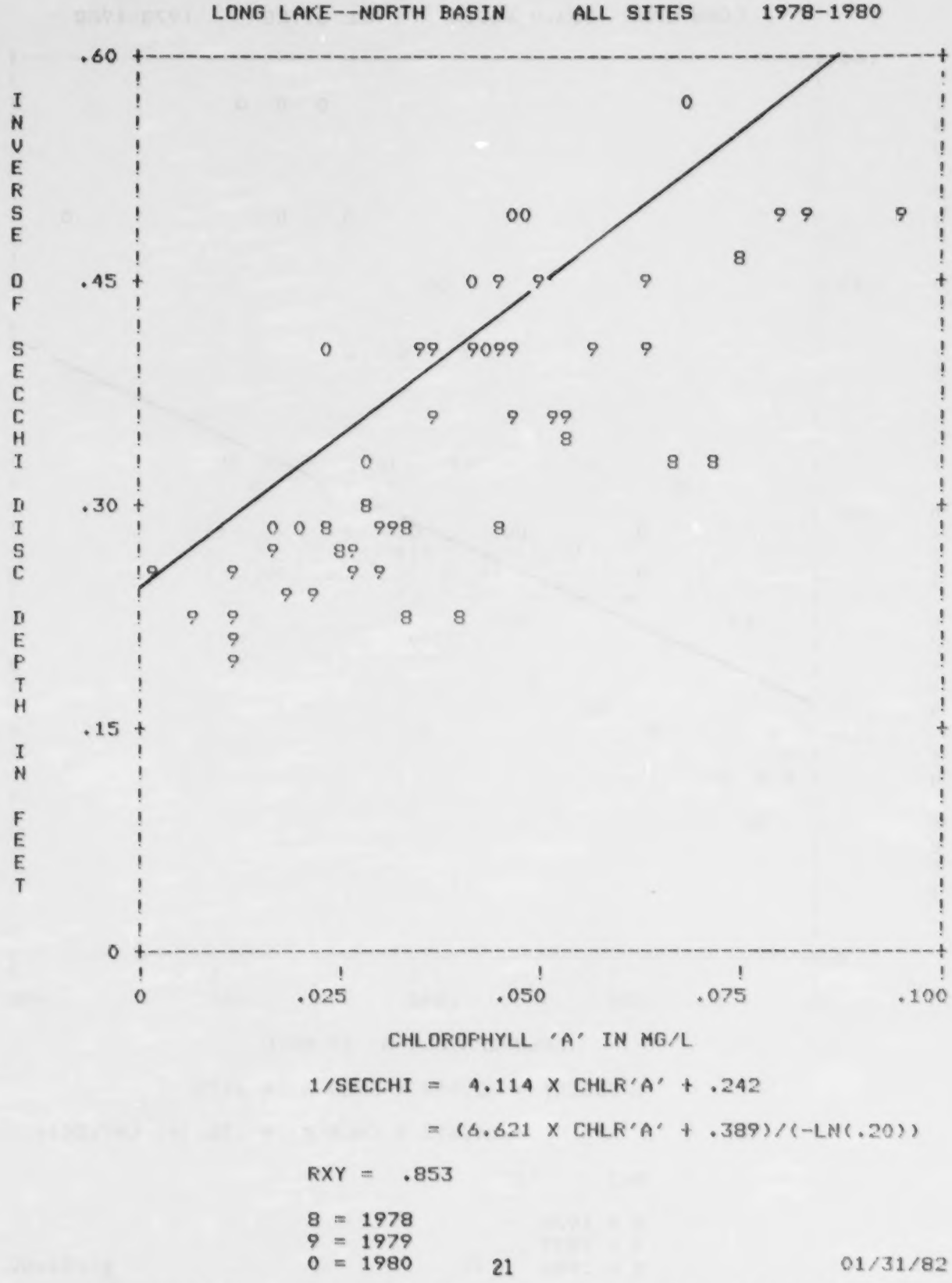
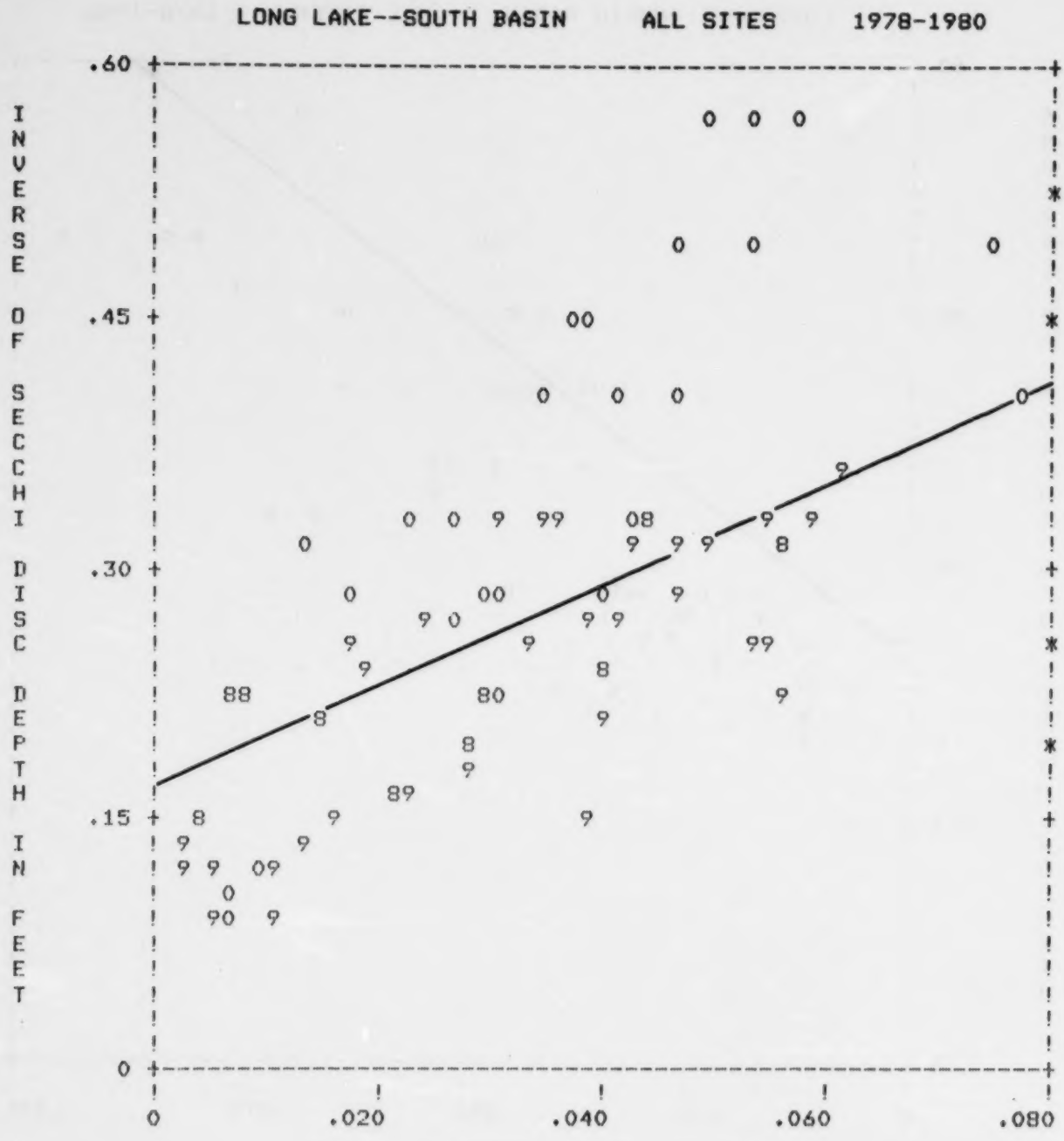


Figure 6. Inverse Secchi disc transparencies versus chlorophyll a concentrations for the north basin of Long Lake.



1/SECCHI = 2.904 X CHLR'A' + .175

= (4.673 X CHLR'A' + .281)/(-LN(.20))

RXY = .635

8 = 1978
9 = 1979
0 = 1980

01/31/82

Figure 7. Inverse Secchi disc transparencies versus chlorophyll a concentrations for the south basin of Long Lake.

Nutrient Limitation

North Basin

TN:TP Ratios. The data for the north basin of Long Lake suggest that nitrogen plays an important role in determining the abundance of phytoplankton. Total nitrogen is present consistently at levels above 1.50 mg/l as shown in Figure 8. Levels are elevated during periods of ice cover due to ammonia release from the sediments. Nitrogen levels, coupled with phosphorus concentrations, result in total nitrogen to total phosphorus ratios shown in Figure 9. Summer TN:TP ratios were 5.2, 13.7 and 16.4 for the years 1978 through 1980. Assuming a ratio of 15 to be the value below which nitrogen limitation is indicated, it is apparent that nitrogen may limit algal abundance. Further indication of that fact is given in the total soluble inorganic nitrogen data (Figure 10). Soluble nitrogen concentrations are depressed in 1978 and 1979. During 1980, however, significant levels of inorganic nitrogen are present. This is probably the reason for the chlorophyll a response to increased total phosphorus concentrations in 1980 that were not observed in 1978. In 1978 total phosphorus levels also rose, but no corresponding rise in chlorophyll was noted. These patterns are shown in Figure 4.

Soluble Nutrients. Nitrogen limitation was suggested for the north basin in 1978 by the results of enrichment experiments as is discussed later. The ortho-phosphate phosphorus data shown in Figure 11 support that suggestion. High concentrations of ortho-phosphate were present in the summer of 1978 and indicate that phosphorus was not limiting. During the summer of 1980, however, phosphate levels were depressed in the presence of significant concentrations of soluble inorganic nitrogen. Because chlorophyll rose in 1980 in response to a rise in total phosphorus, but failed to do so in 1978, suggests that nitrogen is an important factor in the north basin.

6.00
4.50
3.00
1.50
0
TOTAL NITROGEN (mg/l)
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE - NORTH BASIN SITE 2

Figure 8. Epilimnetic (0-2 meters) total nitrogen levels in the north basin of Long Lake.

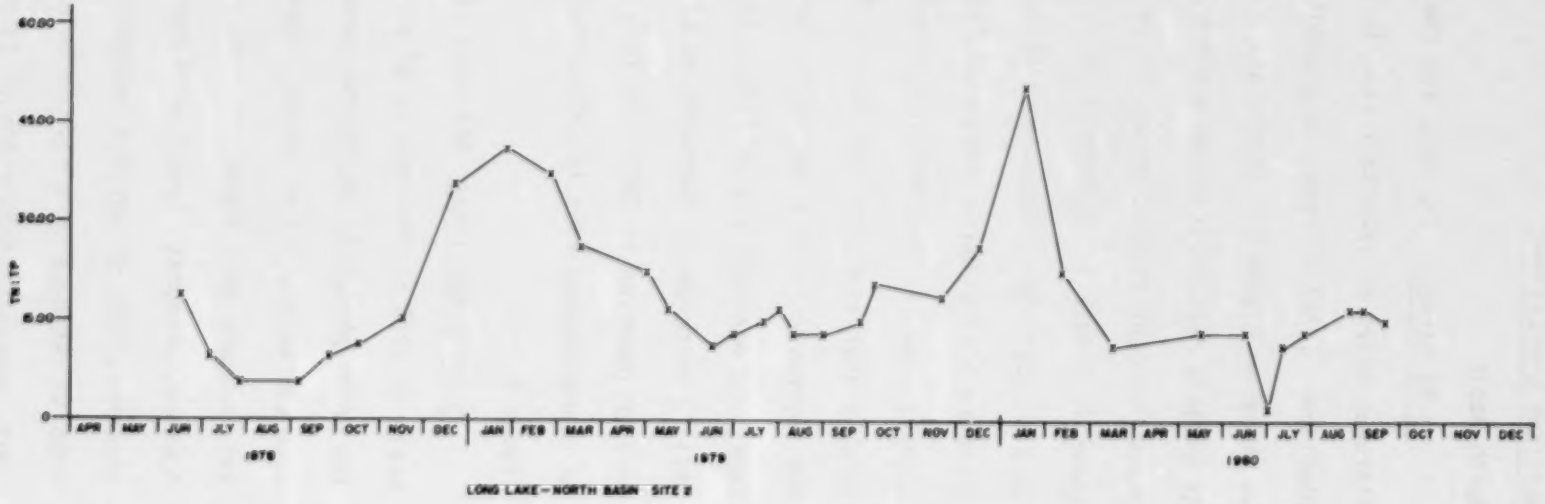

60.00
45.00
30.00
15.00
0
TN:TP
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE - NORTH BASIN SITE 2

Figure 9. Total nitrogen to total phosphorus ratios in the north basin of Long Lake.

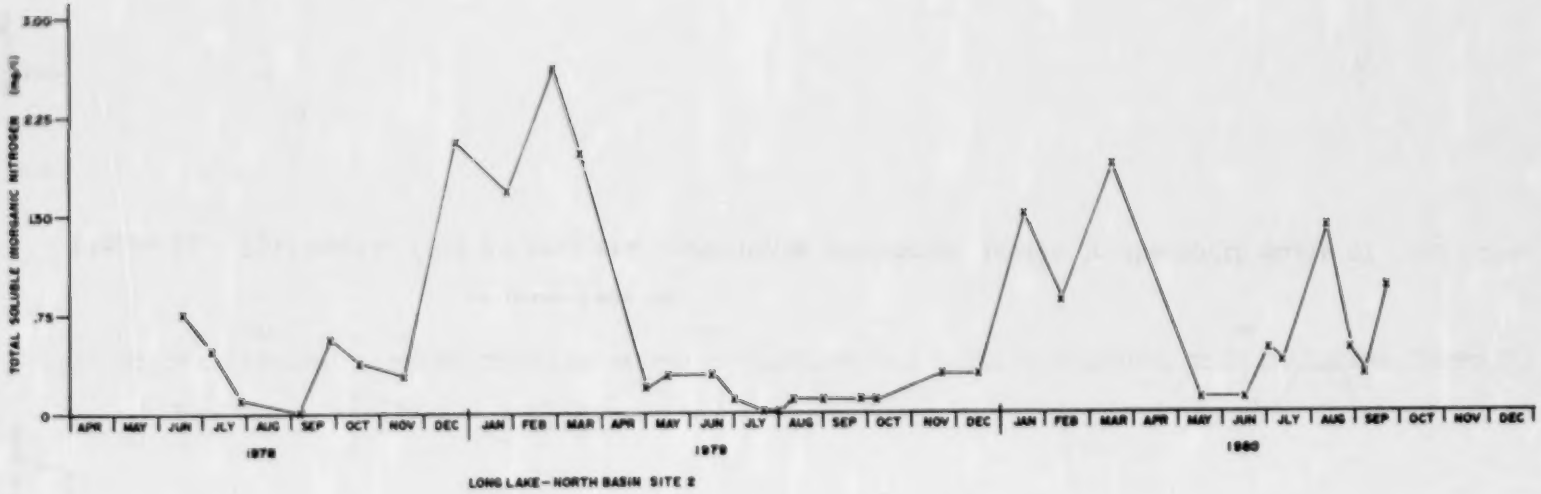

TOTAL SOLUBLE INORGANIC NITROGEN (mg/l)
3.00
2.25
1.50
.75
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE - NORTH BASIN SITE 2

Figure 10. Epilimnetic (0-2 meters) total soluble inorganic nitrogen in the north basin of Long Lake.

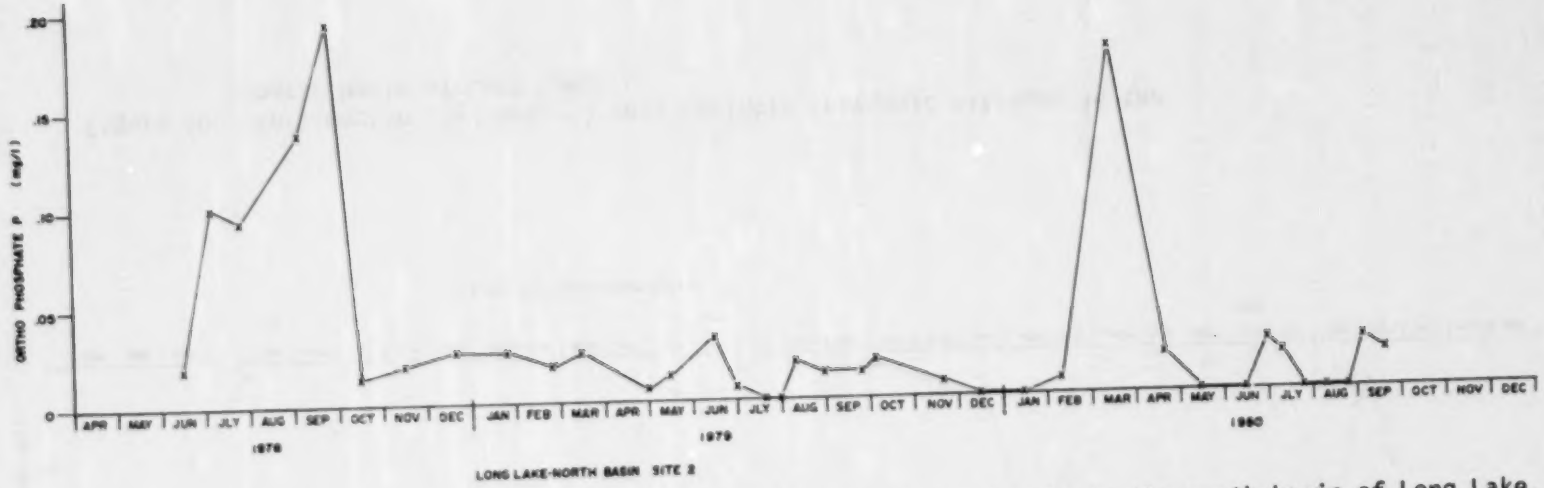

ORTHO PHOSPHATE P (mg/l)
.20
.15
.10
.05
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE-NORTH BASIN SITE 2

Figure 11. Epilimnetic (0-2 meters) ortho-phosphate phosphorus levels in the north basin of Long Lake.

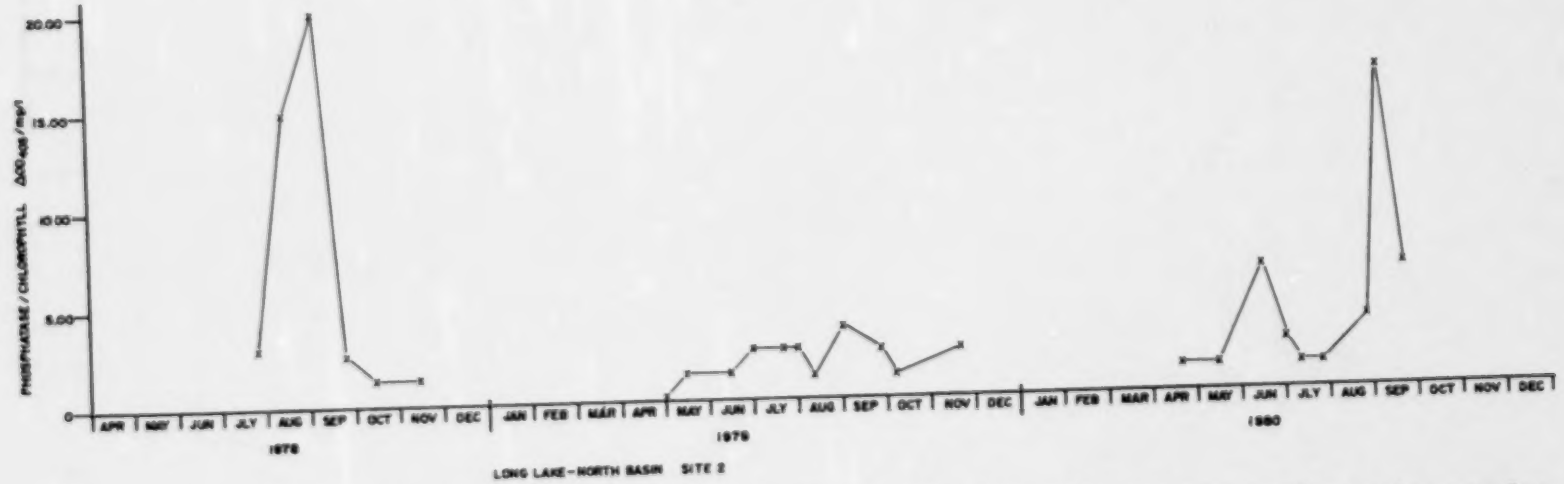

PHOSPHATASE / CHLOROPHYLL Δ 460 nm / mg/l
20.00
15.00
10.00
5.00
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE-NORTH BASIN SITE 2

Figure 12. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of the north basin of Long Lake.

Alkaline Phosphatase. Alkaline phosphatase data for the north basin (Figure 12) are inconclusive. There was some enzyme activity detected in 1978 and 1980. No activity was detected in 1979. Classically the degree of enzyme activity should be inversely related to the ortho-phosphate concentrations, but the patterns shown in Figure 22 are inconsistent.

South Basin

Total nitrogen concentrations in the south basin of Long Lake (Figure 13) are similar to those in the north basin, averaging around 1.50 mg/l. Elevated levels approaching 4.00 mg/l are present during the winter season of 1978-79. Levels during the winter of 1979-80 were less elevated, presumably because of less severe oxygen depletion. Levels during the winter of 1979-80 were less elevated, presumably because of less severe oxygen depletion and increased algae growth in both basins of the lake resulting from less snowfall and greater light penetration.

TN:TP Ratios. The total nitrogen to total phosphorus ratios in the south basin are higher than those in the north basin. Summertime ratios were 9.5, 18.8 and 11.0 for the years 1978 through 1980. These ratios are consistent with the results of enrichment experiments which suggested that phosphorus in combination with nitrogen was generally the limiting factor in the south basin. Nitrogen to phosphorus ratios are presented in Figure 14.

Soluble Nutrients. Soluble nutrient concentrations were depressed in the south basin during the summer periods of active biological growth. Both total soluble inorganic nitrogen and ortho-phosphate phosphorus concentrations declined in all years of this study as are shown in Figures 15 and 16.

Alkaline Phosphatase. Again, alkaline phosphatase activities are inconclusive due to their erratic nature. Activities are generally elevated during periods of depressed ortho-phosphate concentrations in 1978 and 1980.

4.00
3.00
2.00
1.00
0
TOTAL NITROGEN (mg/l)
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE - SOUTH BASIN SITE 5

Figure 13. Epilimnetic (0-2 meters) total nitrogen concentrations in the south basin of Long Lake.

80.00
60.00
40.00
20.00
0
TN:TP
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE - SOUTH BASIN SITE 5

Figure 14. Total nitrogen to total phosphorus ratios in the epilimnetic (0-2 meters) waters of the south basin of Long Lake.

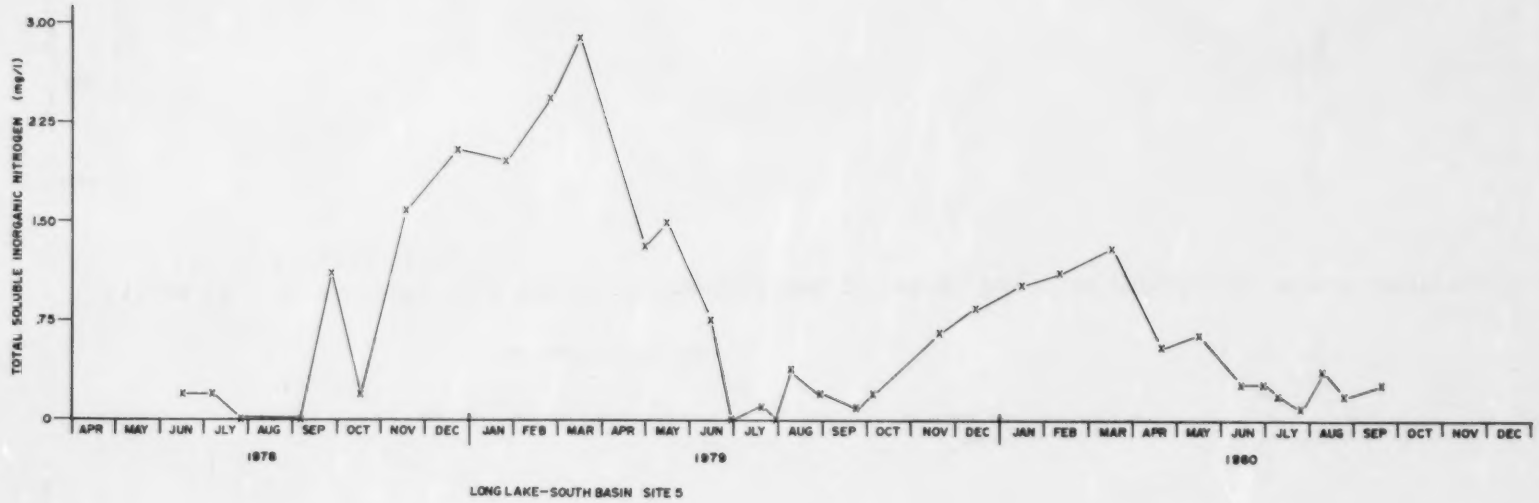

TOTAL SOLUBLE INORGANIC NITROGEN (mg/l)
3.00
2.25
1.50
.75
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE–SOUTH BASIN SITE 5

Figure 15. Epilimnetic (0-2 meters) concentrations of total soluble inorganic nitrogen in the south basin of Long Lake.

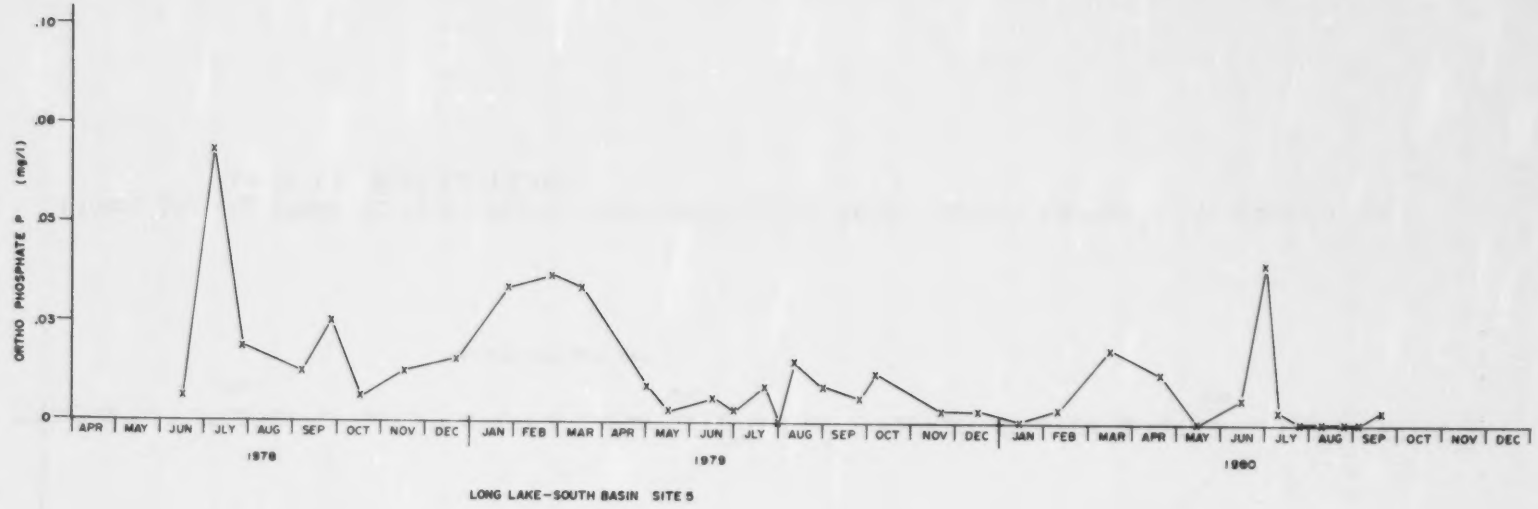

ORTHO PHOSPHATE P (mg/l)
.10
.08
.05
.03
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE-SOUTH BASIN SITE 5

Figure 16. Epilimnetic (0-2 meters) concentrations of ortho-phosphate phosphorus in the south basin of Long Lake.

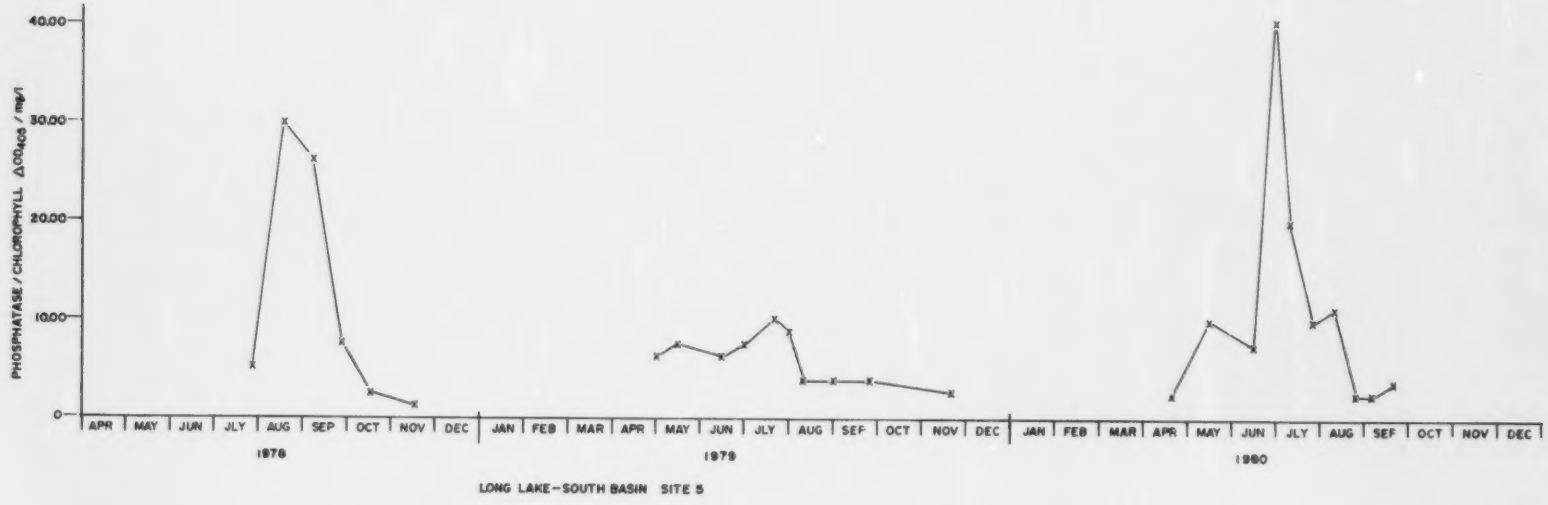

PHOSPHATASE / CHLOROPHYLL Δ OD405 / mg/l
40.00
30.00
20.00
10.00
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
LONG LAKE-SOUTH BASIN SITE 5

Figure 17. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of the south basin of Long Lake.

The data from 1979 show only slight enzyme induction despite low phosphate levels. Alkaline phosphatase data from the south basin of Long Lake are shown in Figure 17.

The water quality of Long Lake during summer periods of this study is summarized in Table 3. The entries represent geometric mean values formed over sampling dates. Complete tabulations of water quality data, in-lake and tributary, appear in Appendices A and B, respectively.

Lake Johanna

Principal Water Quality Indicators

Total phosphorus in Lake Johanna exhibits no distinct annual patterns (Figure 18). Summer total phosphorus concentrations averaged 0.060, 0.056, and 0.090 mg/l for the years 1978 through 1980.

Chlorophyll a data exhibit a distinct annual cycle as shown in Figure 19. Summer maxima are clearly evident. Average summer chlorophyll levels were 0.038, 0.015, and 0.014 mg/l, 1978 through 1980. A major winter peak during the 1979-80 winter reflects the high numbers of Chlamydomonus encountered that winter. Peak winter chlorophyll was 0.070 mg/l that year and exceeded all summer concentrations observed for Johanna Lake during the study.

Nutrient Limitation

Ortho-phosphate phosphorus concentrations are depressed during summer periods in Lake Johanna. Average summer phosphate levels were 0.014, 0.006 and 0.016 mg/l, during the years 1978-1980. These data are shown in Figure 20. A winter peak in phosphate concentration approaching 0.040 mg/l is evident and seems to be related to sediment phosphorus release during the winter of 1978-1979 when deep snows limited light penetration and, subsequently, algae growth. Less oxygen depletion and increased algae growth were observed during the winter of 1979-1980 when snow depths were considerably less.

Table 3. Summary of geometric mean water quality conditions for Long Lake. Annual averages were calculated over sampling dates during the July through September periods.

Year	Site	Secchi Disc (m)	Chlorophyll "a" (mg/l)	Total Phosphorus (mg P/l)	Dissolved Phosphorus (mg P/l)	Ortho Phosphorus (mg P/l)	Nitrate Nitrite Nitrogen (mg N/l)	Ammonia Nitrogen (mg N/l)	Total Kjeldahl Nitrogen (mg N/l)	TN:TP	Alkalinity (mg $CaCO_3$/l)
NORTH BASIN - LONG LAKE											
1978	1	0.65									
	2	0.88	.087	.319	.226	.251	.179	.156	1.473	5.2	64
	3	0.75									
1979	1	0.80	.049	.127	.053	.005	.022	.024	1.716	13.7	144
	2	0.74	.044	.131	.038	.007	.026	.026	1.774	13.7	144
	3	0.71	.057	.115	.040	.005	.022	.048	1.804	15.9	131
1980	1	0.26	.170	.451	.082	.004	.070	.449	5.011	11.3	118
	2	0.29	.167	.283	.020	.004	.057	.434	4.575	16.4	119
	3	0.29	.118	.218	.035	.005	.080	.288	3.967	18.6	113
SOUTH BASIN - LONG LAKE											
1978	4	0.87									
	5	0.94	.059	.136	.142	.084	.068	.167	1.219	9.5	50
	6	0.88									
1979	4	1.03	.046	.082	.037	.004	.020	.048	1.582	19.5	123
	5	1.01	.046	.087	.036	.005	.017	.057	1.615	18.8	123
	6	1.13	.041	.089	.036	.005	.018	.087	1.637	18.6	126
1980	4	0.66	.045	.169	.019	.006	.047	.233	1.785	10.8	114
	5	0.75	.053	.152	.017	.002	.046	.173	1.627	11.0	113
	6	0.70	.054	.232	.033	.001	.044	.103	1.544	6.8	114

TOTAL PHOSPHORUS (mg/l)
.12
.09
.06
.03
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 18. Lake Johanna epilimnetic (0-2 meters) concentrations of total phosphorus.

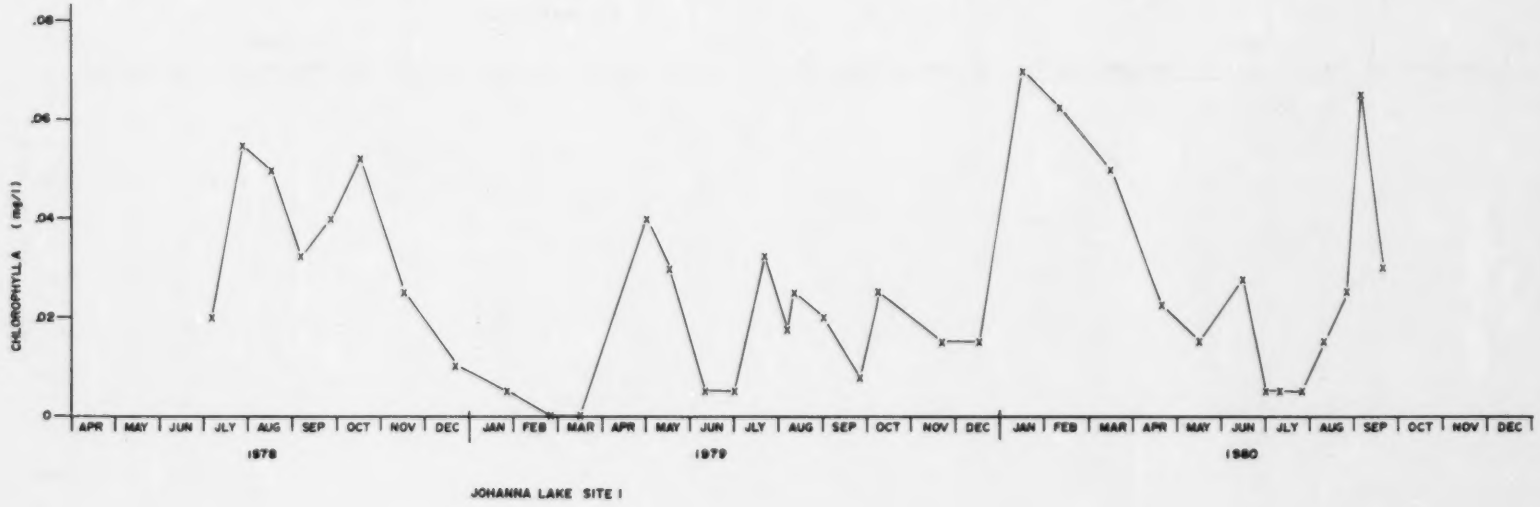

CHLOROPHYLLA (mg/l)
.08
.06
.04
.02
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 19. Lake Johanna epilimnetic (0-2 meters) chlorophyll a concentrations.

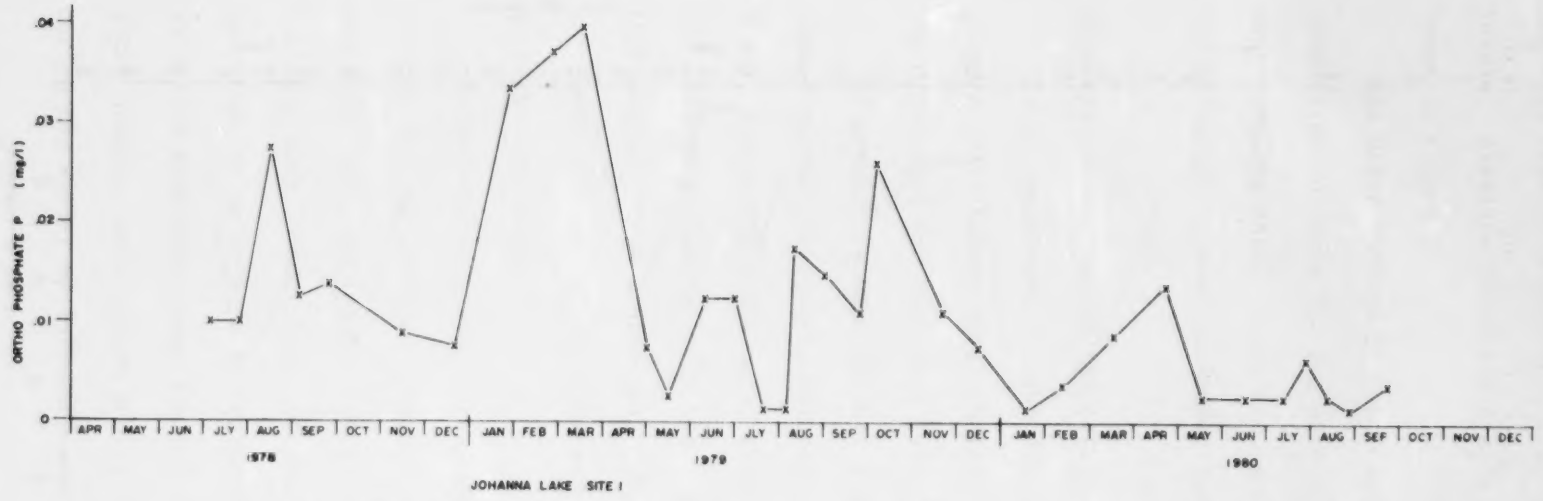

ORTHO PHOSPHATE P (mg/l)
.04
.03
.02
.01
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 20. Epilimnetic (0-2 meters) ortho-phosphate phosphorus concentrations in Lake Johanna.

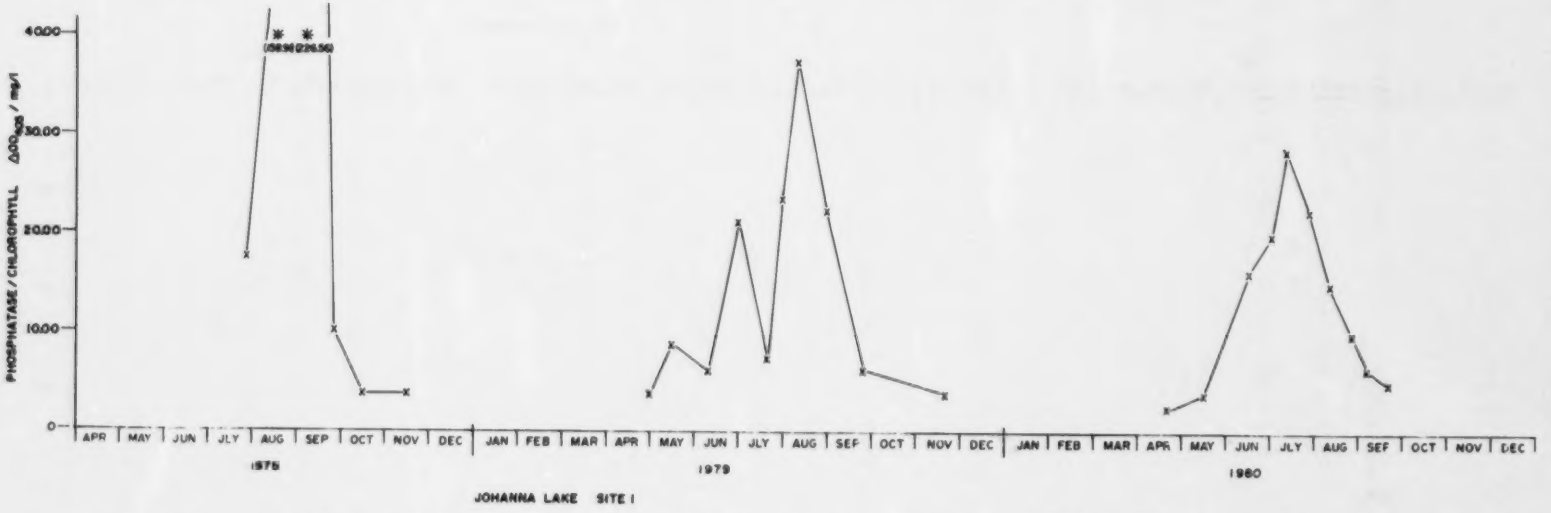

PHOSPHATASE / CHLOROPHYLL
40.00
30.00
20.00
10.00
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 21. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of Lake Johanna.

Annual summer increases in alkaline phosphatase activity were observed during periods of depressed ortho-phosphate concentrations during all summers of the study (Figure 21).

Total nitrogen levels in Lake Johanna averaged approximately 1.00 mg/l as shown in Figure 22. Total nitrogen to total phosphorus ratios averaged 14.7, 17.9 and 12.1 during 1978, 1979 and 1980, respectively. Those data are depicted in Figure 23. Coupled with alkaline phosphatase data, TN:TP ratios imply that Lake Johanna is phosphorus-limited. There are periods of inorganic nitrogen depletion also, suggesting that multiple nutrient limitation is probable. These periods, shown in Figure 24, occur during the summers of this study.

Water quality data for Lake Johanna are summarized in Table 4 for the summer periods of this study. Geometric mean data are presented for individual sampling stations. Water chemistry data are tabulated in Appendix A of this report.

Lake Josephine

Principal Water Quality Indicators

Total phosphorus concentrations in Lake Josephine average approximately 0.060 mg/l with little apparent seasonal variation (Figure 25). This pattern is similar to that shown by Lake Johanna, and dissimilar to patterns observed in data from both basins of Long Lake. There are distinct summer chlorophyll maxima in all years of the study as shown in Figure 26. Average summer chlorophyll concentrations were 0.030, 0.009 and 0.011 mg/l, 1978 through 1980.

Nutrient Limitation

Ortho-phosphate phosphorus concentrations were low during the summer of 1980, averaging 0.003 mg/l. Levels were not depressed during 1978 and 1979, averaging 0.019, and 0.012 mg/l, as shown in Figure 27. Alkaline phosphatase

Table 4. Summary of geometric mean water quality conditions for Lake Johanna. Annual averages were calculated over sampling dates during the July through September periods.

Year	Site	Secchi Disc (m)	Chlorophyll "a" (mg/l)	Total Phosphorus (mg P/l)	Dissolved Phosphorus (mg P/l)	Ortho Phosphorus (mg P/l)	Nitrate Nitrit Nitrogen (mg N/l)	Ammonia Nitrogen (mg N/l)	Total Kjeldahl Nitrogen (mg N/l)	TN:TP	Alkalinity (mg $CaCO_3$/l)
JOHANNA LAKE											
1978	1	0.94	.038	.060	.054	.014	.006	.023	.878	14.7	88
	2	0.93									
1979	1	1.56	.015	.056	.063	.006	.007	.020	.995	17.9	89
	2	1.52	.019	.051	.031	.009	.007	.023	.922	18.2	89
1980	1	2.02	.014	.093	.013	.016	.028	.082	1.099	12.1	85
	2	2.14	.013	.077	.012	.003	.033	.055	.969	13.0	85

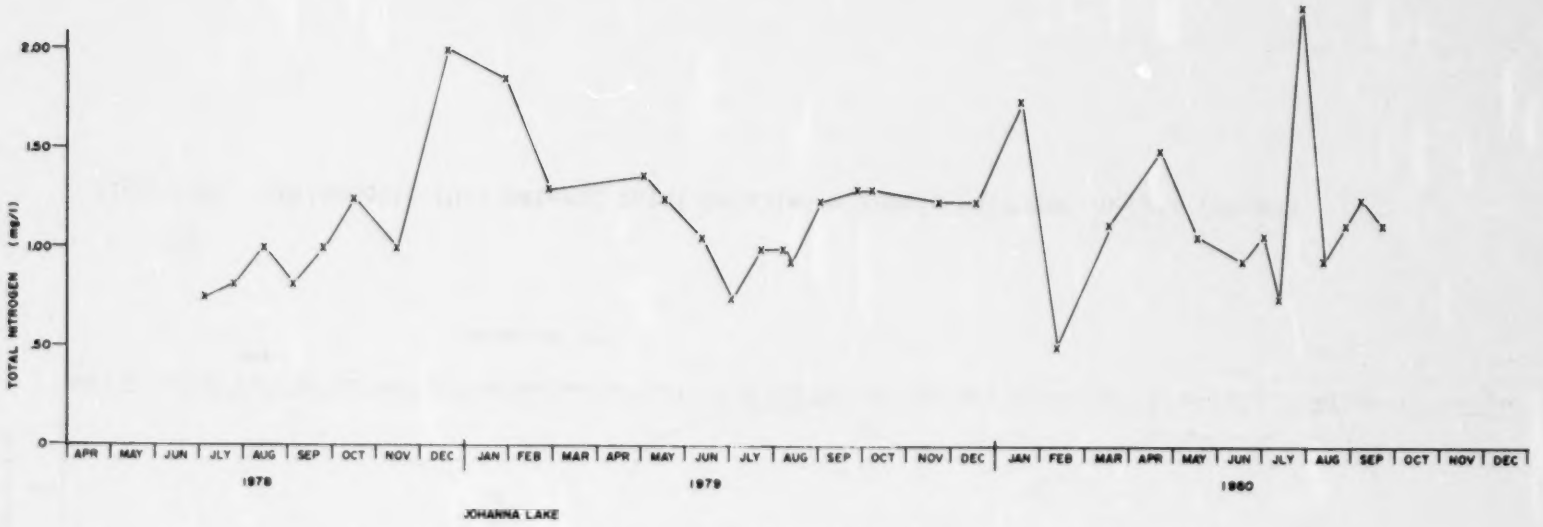

TOTAL NITROGEN (mg/l)
2.00
1.50
1.00
.50
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE

Figure 22. Lake Johanna epilimnetic (0-2 meters) concentrations of total nitrogen.

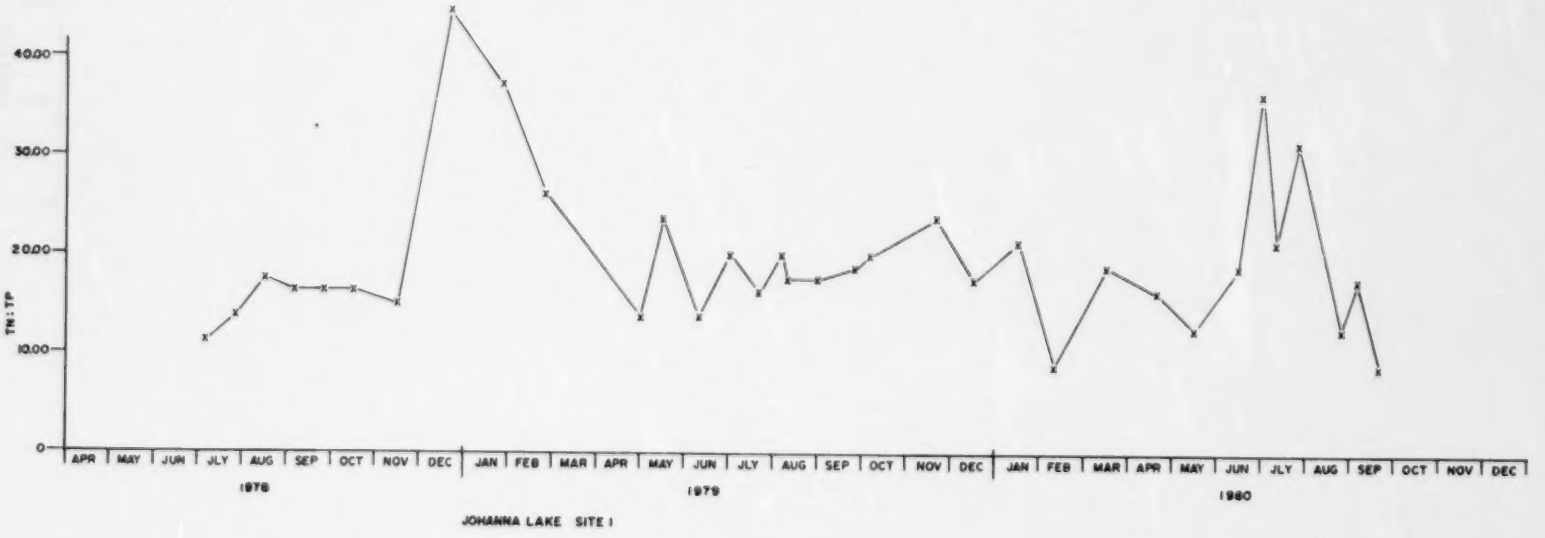

TN:TP
40.00
30.00
20.00
10.00
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 23. Total nitrogen to total phosphorus ratios in Lake Johanna.

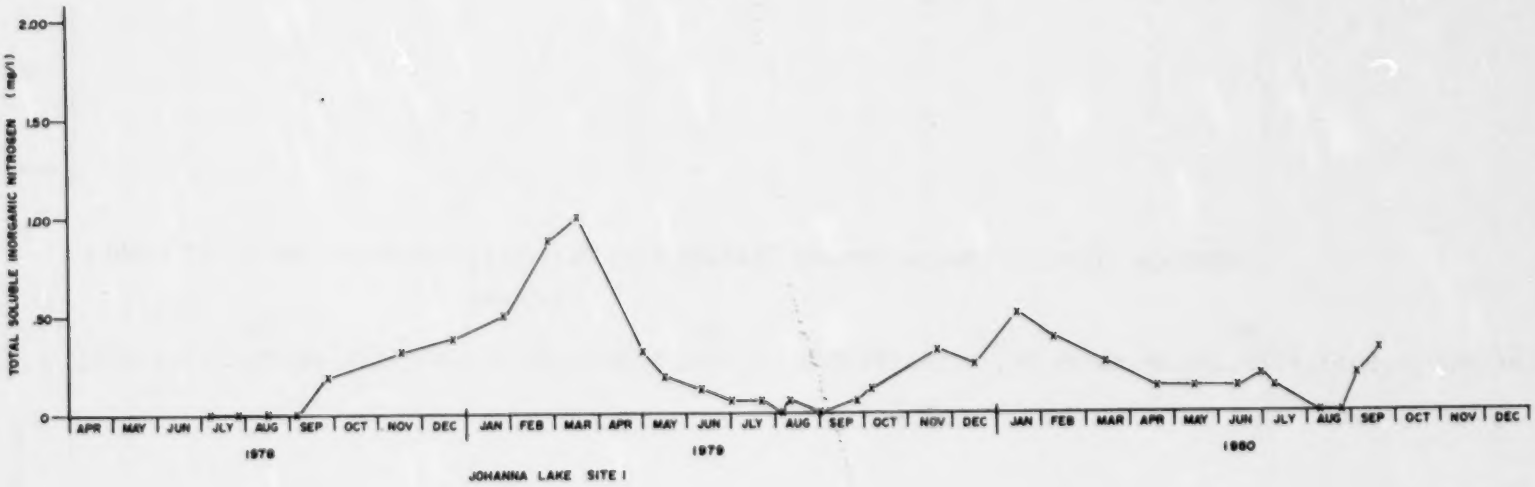

TOTAL SOLUBLE INORGANIC NITROGEN (mg/l)
2.00
1.50
1.00
.50
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOHANNA LAKE SITE I

Figure 24. Epilimnetic (0-2 meters) total soluble inorganic nitrogen in Lake Johanna.

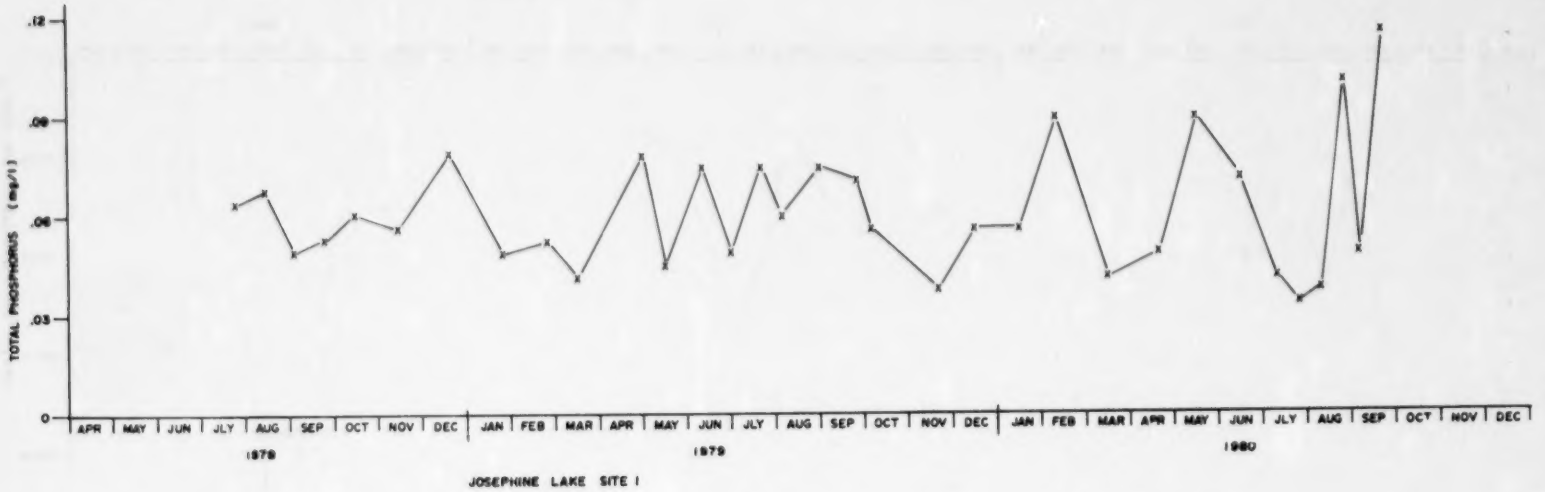

TOTAL PHOSPHORUS (mg/l)
.12
.09
.06
.03
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 25. Lake Josphine epilimnetic (0-2 meters) total phosphorus concentrations.

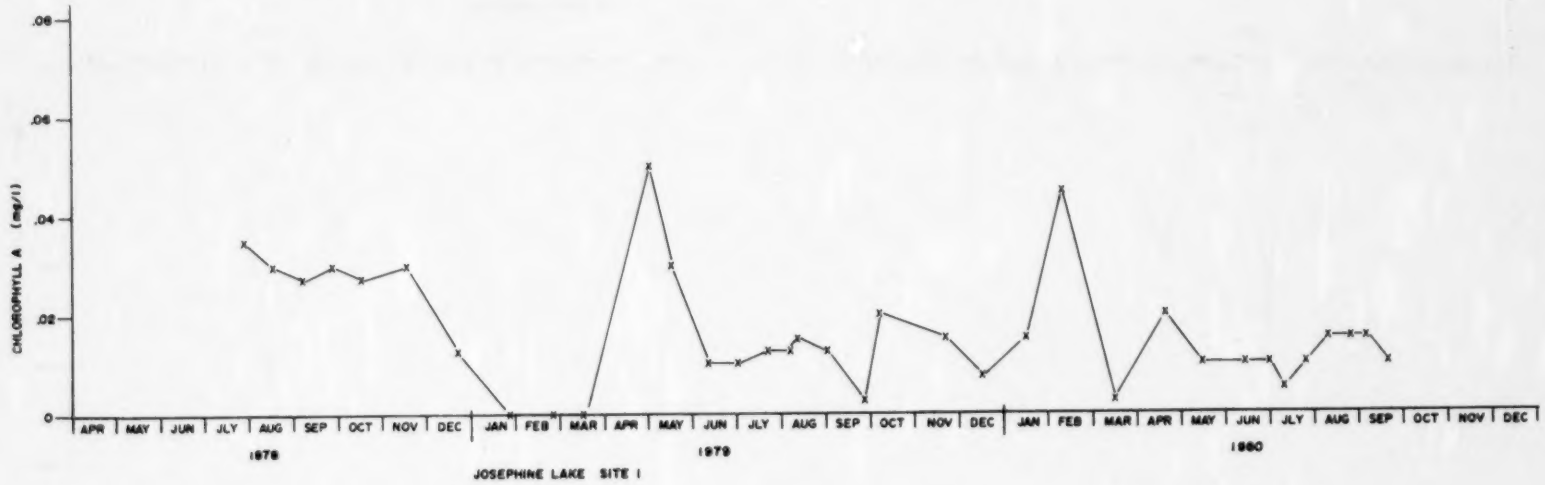

CHLOROPHYLL A (mg/l)
.08
.06
.04
.02
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 26. Lake Josephine epilimnetic (0-2 meters) concentrations of chlorophyll *a*.

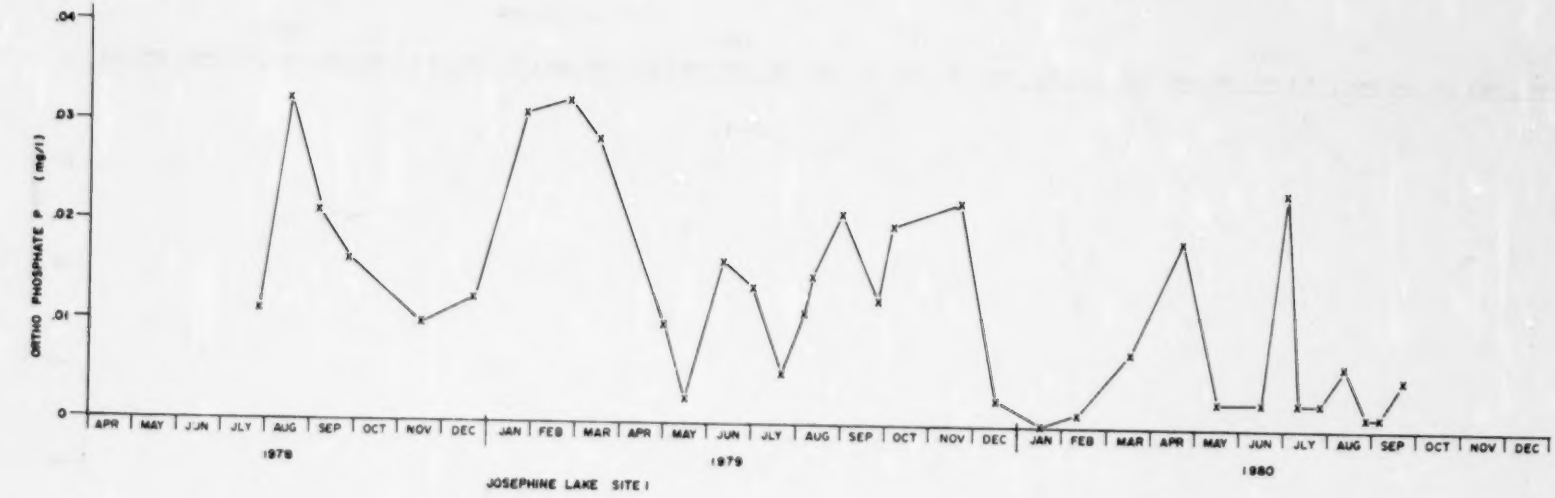

ORTHO PHOSPHATE P (mg/l)
.04
.03
.02
.01
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 27. Epilimnetic (0-2 meters) ortho-phosphate phosphorus concentrations in Lake Josephine.

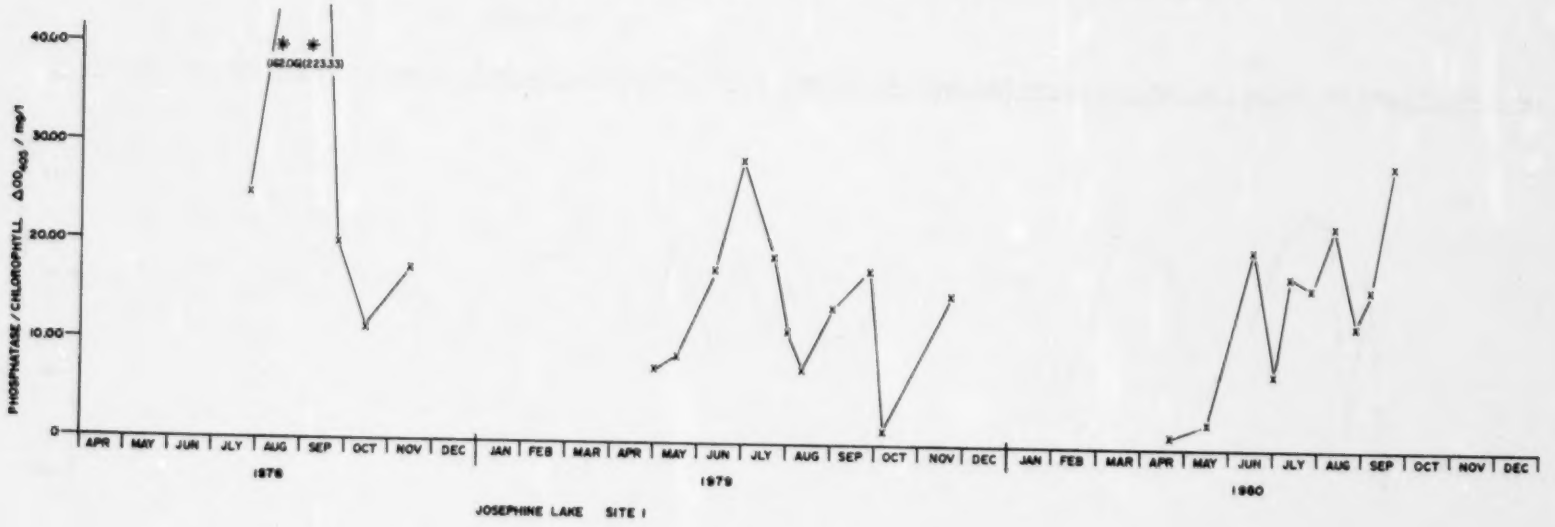

PHOSPHATASE / CHLOROPHYLL Δ OD455 / mg/l
40.00
30.00
20.00
10.00
0
(62.06)(223.33)
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 28. Alkaline phosphatase enzyme activity in phytoplankton collected from surface water samples of Lake Josephine.

activities, however, increased during the summer periods of all years (Figure 28). In that respect, these data are inconsistent. Both orthophosphate concentrations and alkaline phosphatase levels are alternately high and low through the summers of 1978 and 1979, with no apparent patterns. The data do not suggest strong phosphorus limitation.

Annual average total nitrogen concentrations shown in Figure 29 exceed 1.00 mg/l. A maximum of 2.51 mg/l was observed on 20 December 1978. The observed rise during the winter of 1978-1979 is attributable to sediment ammonia release. Total nitrogen to total phosphorus ratios averaged in excess of 15 on an annual basis (Figure 30). Summer TN:TP ratios for the years 1978 through 1980 were 15.4, 9.6 and 9.8 mg/l. These data do not strongly suggest phosphorus limitation. Depressed inorganic nitrogen levels during summer periods (Figure 31) also argue against phosphorus limitation.

Geometric mean water quality conditions during summer periods are summarized in Table 5. On the basis of these data, and the preceeding observations, combined nitrogen and phosphorus limitation has been assessed for Lake Josephine. Water chemistry data are tabulated and appear in Appendix A of this report.

Phytoplankton

Long Lake

Chlorophyll a concentrations in Long Lake north averaged .087, .044 and .167 mg/l in 1978, 1979 and 1980, respectively, with 1980 clearly having the highest concentrations. Long Lake south generally had lower concentrations, .059, .046 and .053 mg/l from 1978 to 1980, respectively (Figure 32). The highest single concentration in Long Lake north was .276 mg/l on July 13, 1980, considerably greater than the high of .143 mg/l in Long Lake south on September 6, 1978.

Table 5. Summary of geometric mean water quality conditions for Lake Josephine. Annual averages were calculated over sampling dates during the July through September periods.

Year	Site	Secchi Disc (m)	Chlorophyll "a" (mg/l)	Total Phosphorus (mg P/l)	Dissolved Phosphorus (mg P/l)	Ortho Phosphorus (mg P/l)	Nitrate Nitrite Nitrogen (mg N/l)	Ammonia Nitrogen (mg N/l)	Total Kjeldahl Nitrogen (mg N/l)	TN:TP	Alkalinity (mg $CaCO_3$/l)
JOSEPHINE LAKE											
1978	1	0.81	.030	.059	.085	.019	.007	.014	.899	15.4	91
	2	0.82									
1979	1	1.16	.009	.103	.072	.012	.010	.032	.976	9.6	112
	2	1.21	.011	.062	.039	.015	.008	.020	.972	15.8	114
1980	1	1.38	.011	.084	.016	.003	.036	.020	.799	9.9	107
	2	1.17	.010	.074	.016	.003	.029	.019	.817	11.4	107

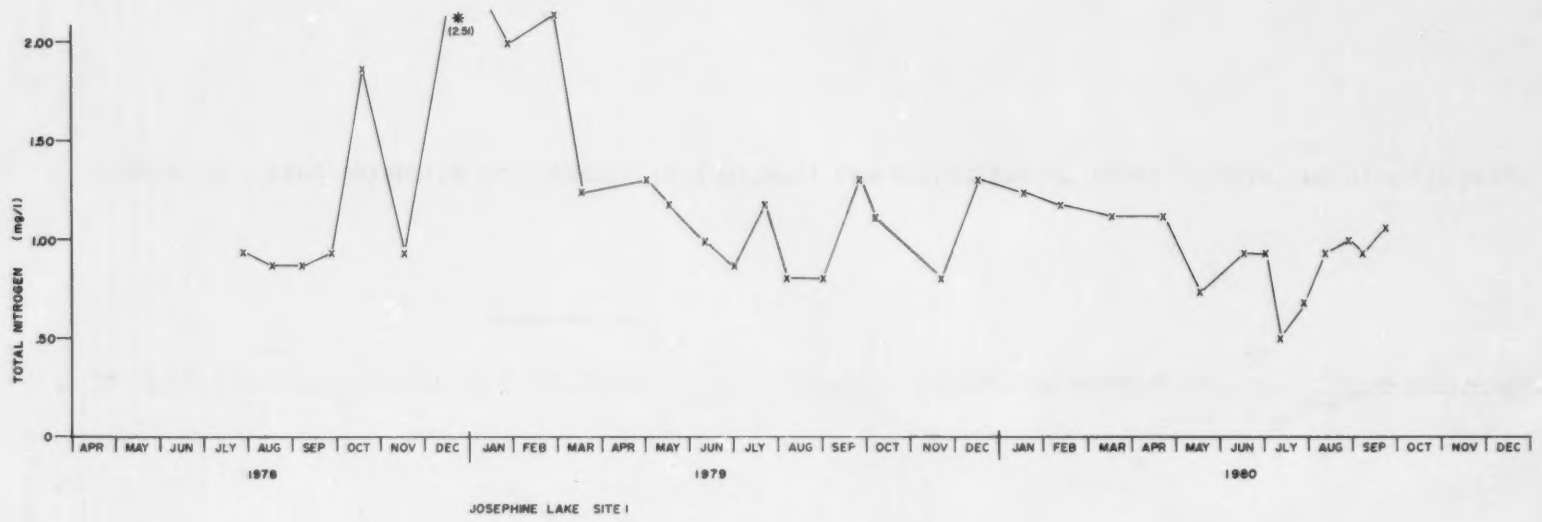


Figure 29. Lake Josephine epilimnetic (0-2 meters) total nitrogen concentrations.

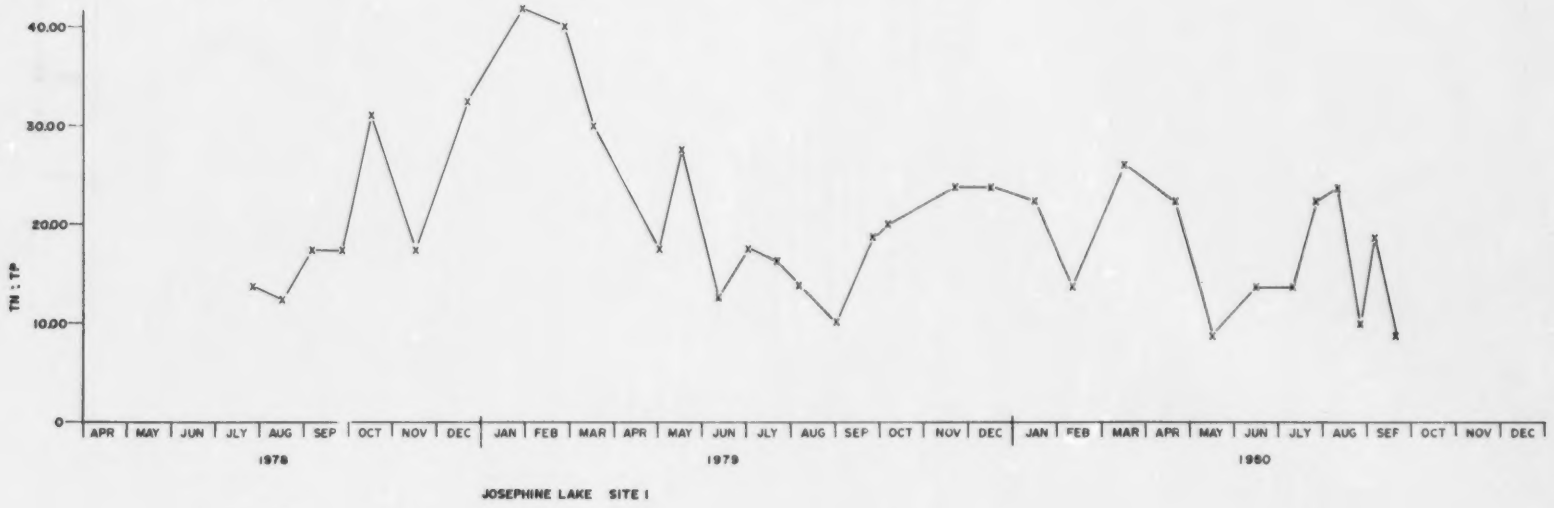

TN : TP
40.00
30.00
20.00
10.00
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 30. Total nitrogen to total phosphorus ratios in Lake Josephine.

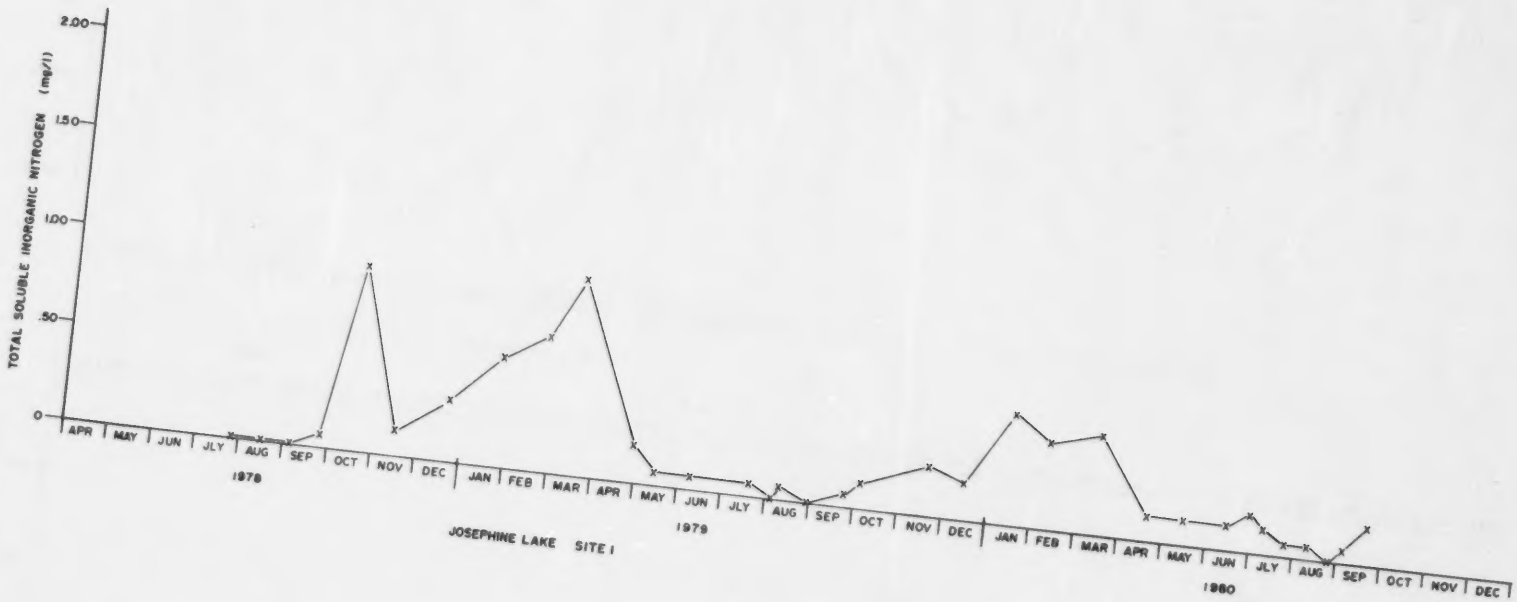

TOTAL SOLUBLE INORGANIC NITROGEN (mg/l)
2.00
1.50
1.00
.50
0
APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JLY AUG SEP OCT NOV DEC
1978
1979
1980
JOSEPHINE LAKE SITE I

Figure 31. Lake Josephine epilimnetic (0-2 meters) concentrations of total soluble inorganic nitrogen.

Figure 32. Occurrence and abundance of major phytoplankton taxa in the south basin of Long Lake.

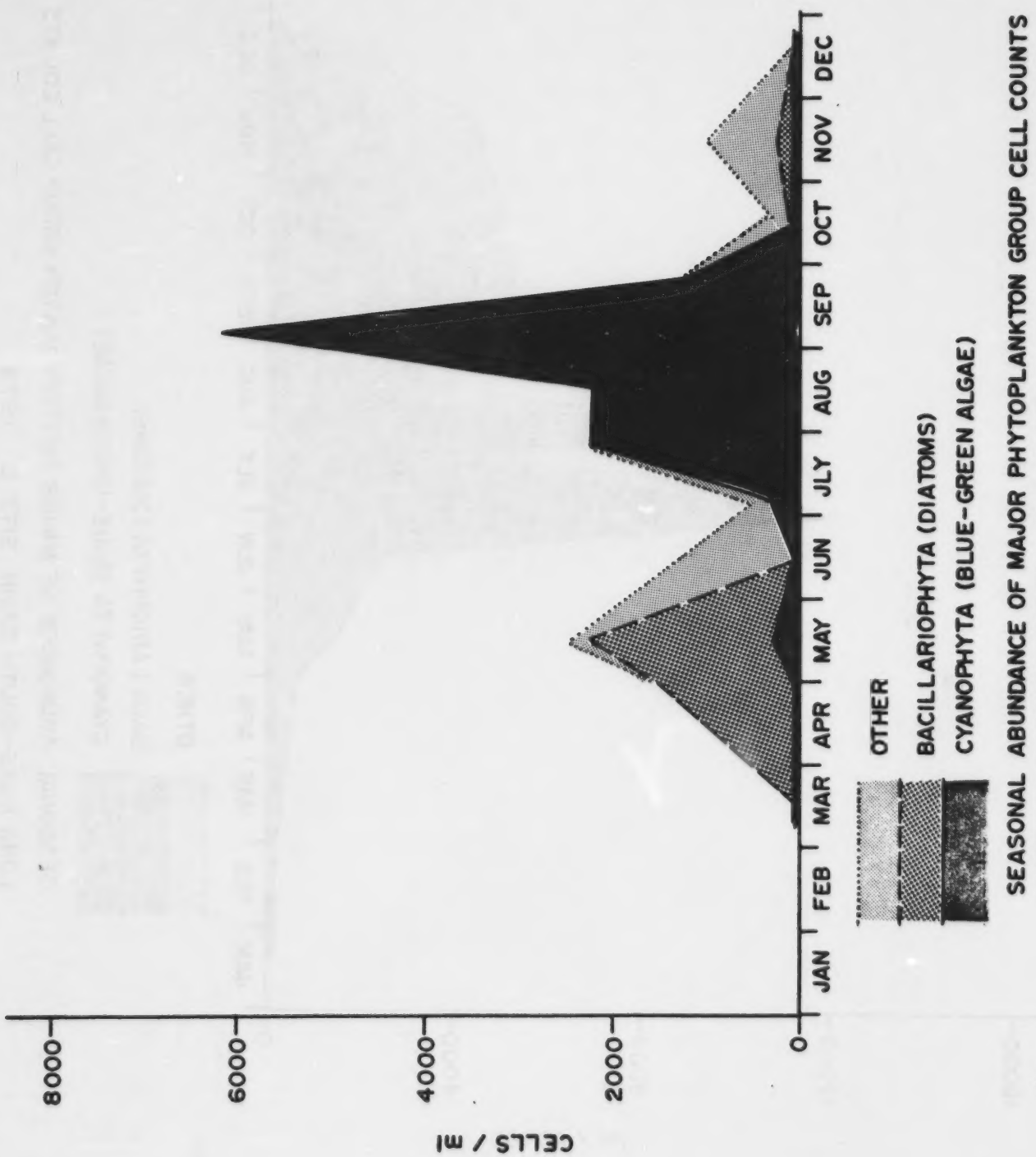


Figure 32. Occurrence and abundance of major phytoplankton taxa in the south basin of Long Lake. (Continued)

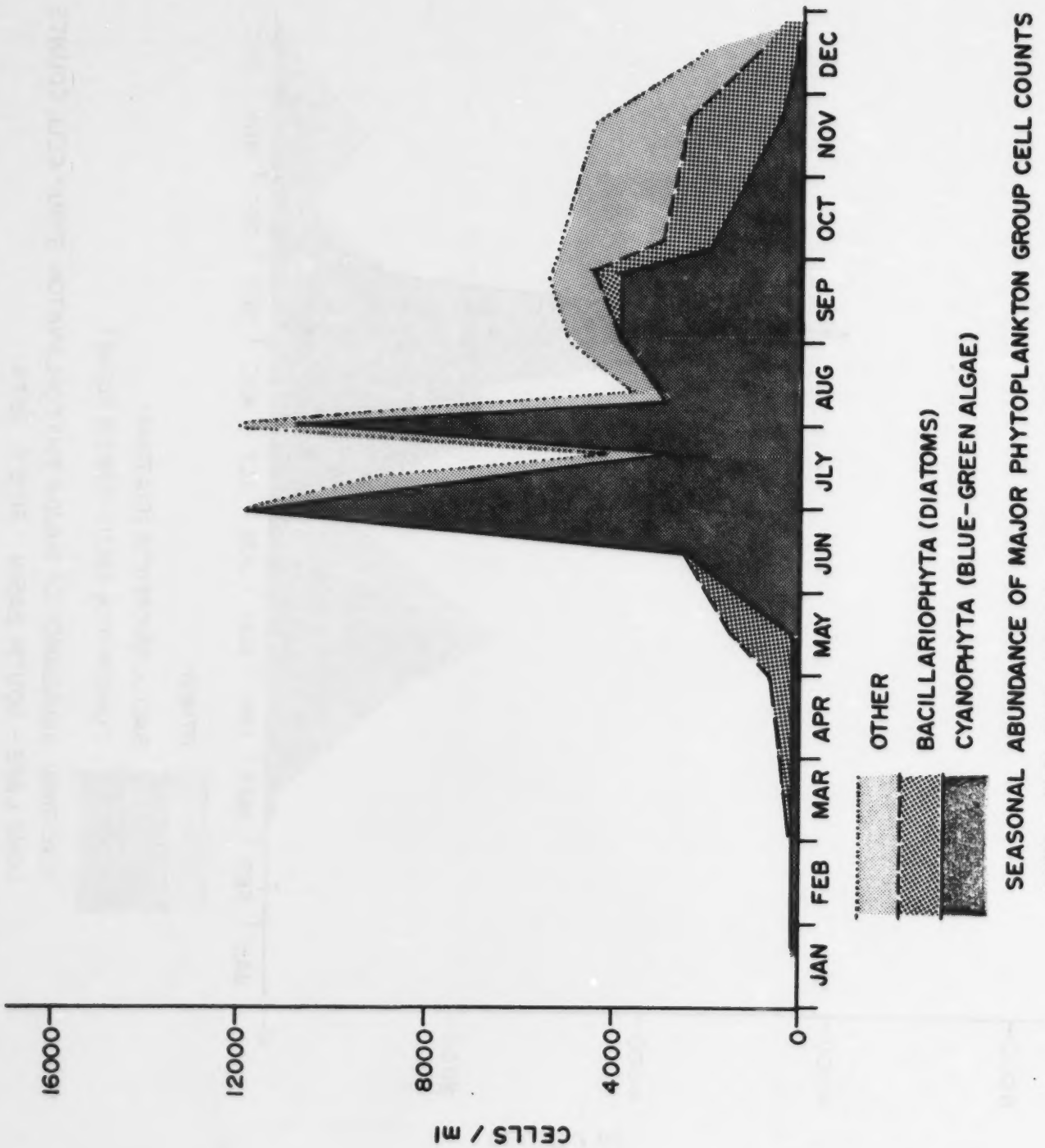
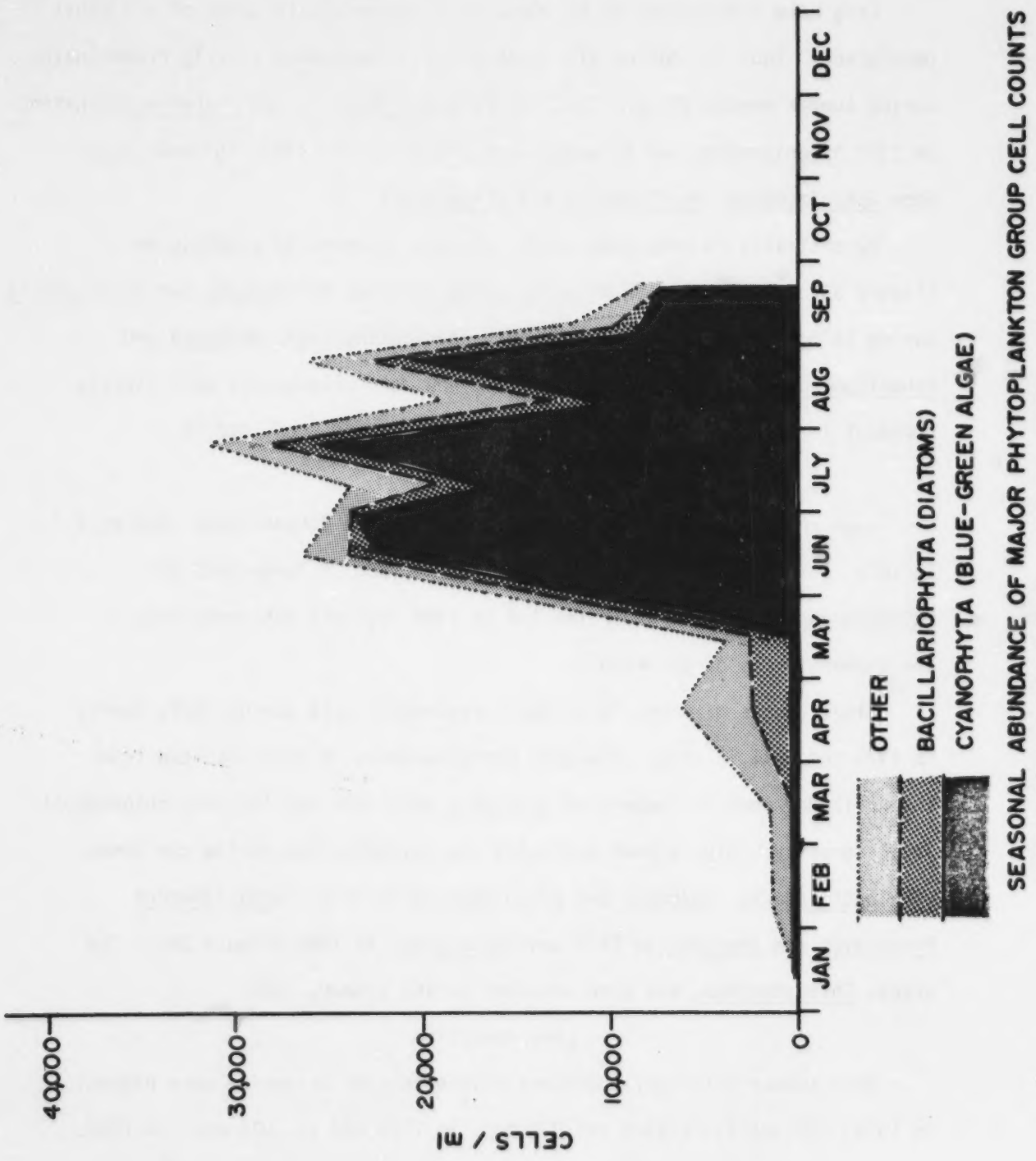


Figure 32. Occurrence and abundance of major phytoplankton taxa in the south basin of Long Lake. (Continued)



Chlorophyll appears to correlate well with algal counts in Long Lake north and south in all three years, although the correlation is not perfect probably because the cells vary considerably in size.

Long Lake south seems to be classically eutrophic in terms of its algal population. That is, during all three years, blue-greens clearly predominated during summer months (Figure 32). In 1978 Oscillatoria and Anabaena dominated. In 1979 Aphanizomenon and Anabaena were dominant. In 1980, the main algae were Aphanizomenon, Oscillatoria and Chroococcus.

By contrast, in Long Lake north, diatoms appeared to predominate (Figure 33) in numbers with Melosira being dominant to Anabaena and Oscillatoria during 1978, and Cyclotella and Melosira dominating over Anabaena and Aphanizomenon during 1979. During 1980, however, blue-greens were clearly dominant in Long Lake north, especially Anabaena and Oscillatoria.

Lake Johanna

Mean summer chlorophyll concentrations in Lake Johanna were .038 mg/l in 1978, .015 mg/l in 1979, and .014 mg/l in 1980. A large peak of Chlamydomonas developed under the ice in 1980, but did not contribute to the summer levels of chlorophyll.

Algal counts mirrored chlorophyll reasonably well during 1978, poorly in 1979 and well in 1980. The poor correspondence in 1979 resulted from the April-May peak in numbers of Nitzschia which did not increase chlorophyll levels greatly. Blue-greens dominated the phytoplankton during the summer with Oscillatoria, Anabaena and Aphanizomenon in 1978. Aphanizomenon, Phormidium and Anabaena in 1979 and Chroococcus in 1980 (Figure 34). The green, Chlamydomonas, was also abundant during summer, 1980.

Lake Josephine

Mean summer chlorophyll concentrations in Lake Josephine were highest in 1978, .030 mg/l, falling to .009 mg/l in 1979 and to .011 mg/l in 1980.

Figure 33. Occurrence and abundance of major phytoplankton taxa in the north basin of Long Lake.

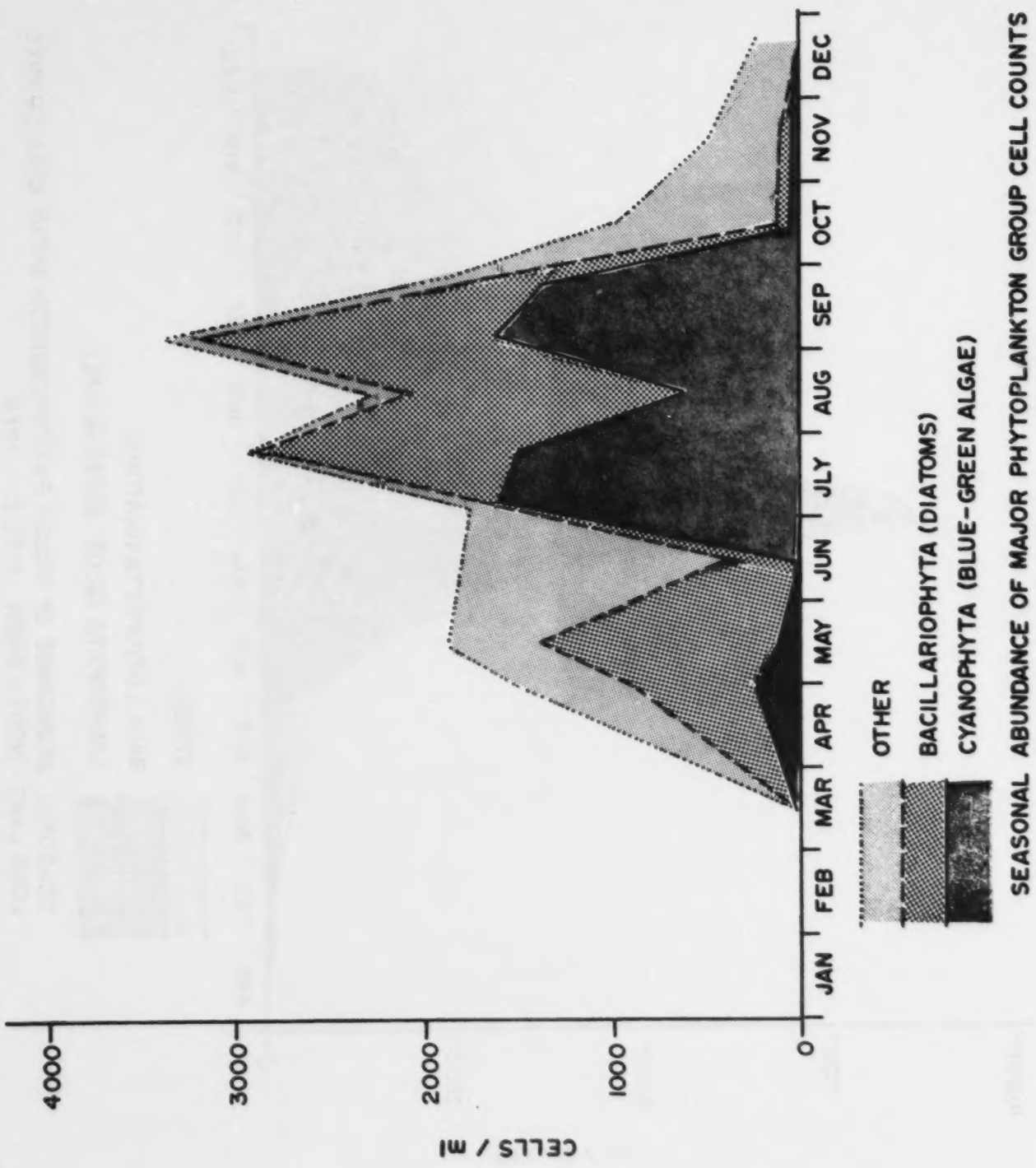


Figure 33. Occurrence and abundance of major phytoplankton taxa in the north basin of Long Lake. (Continued)

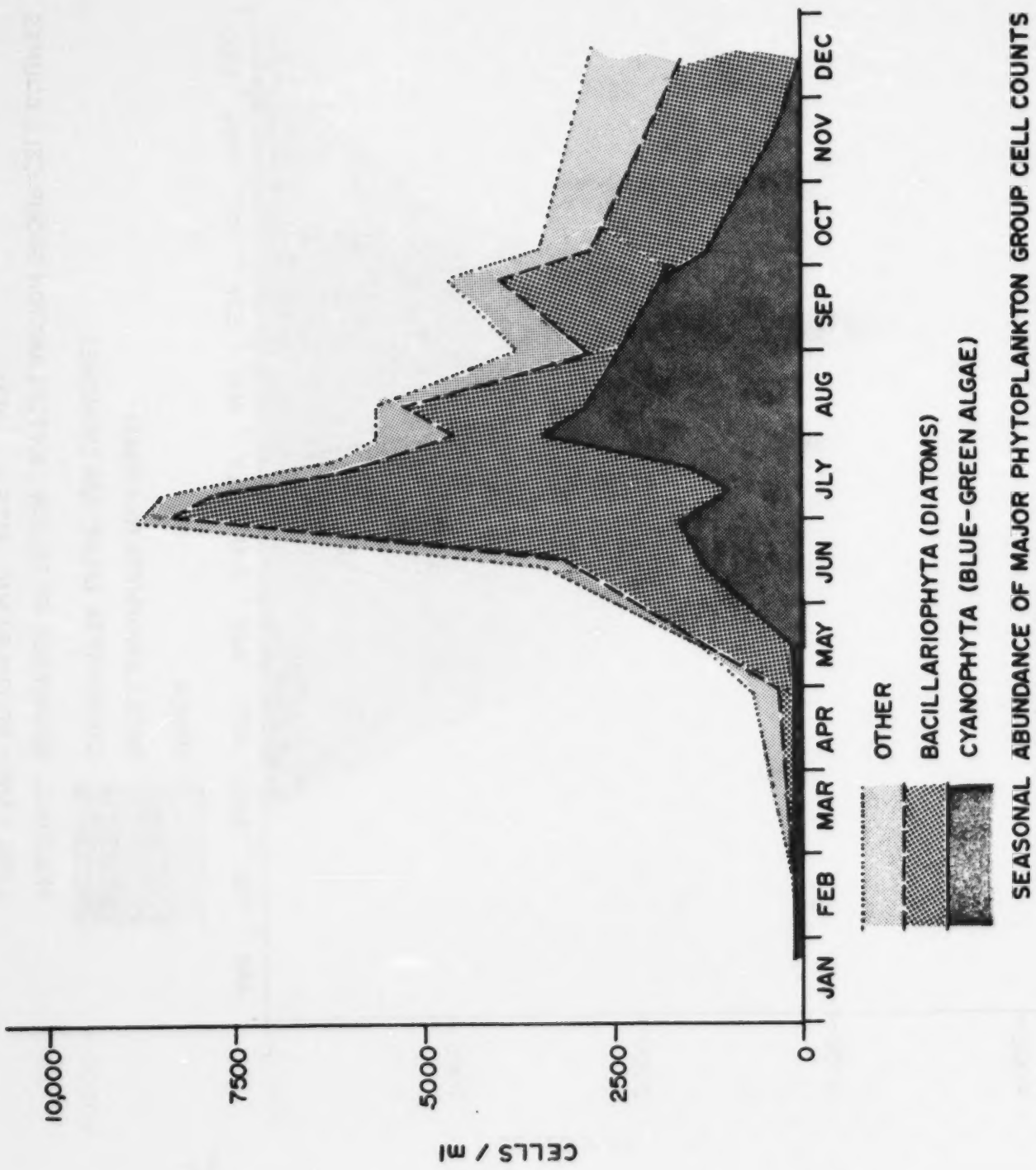


Figure 33. Occurrence and abundance of major phytoplankton taxa in the north basin of Long Lake. (Continued)

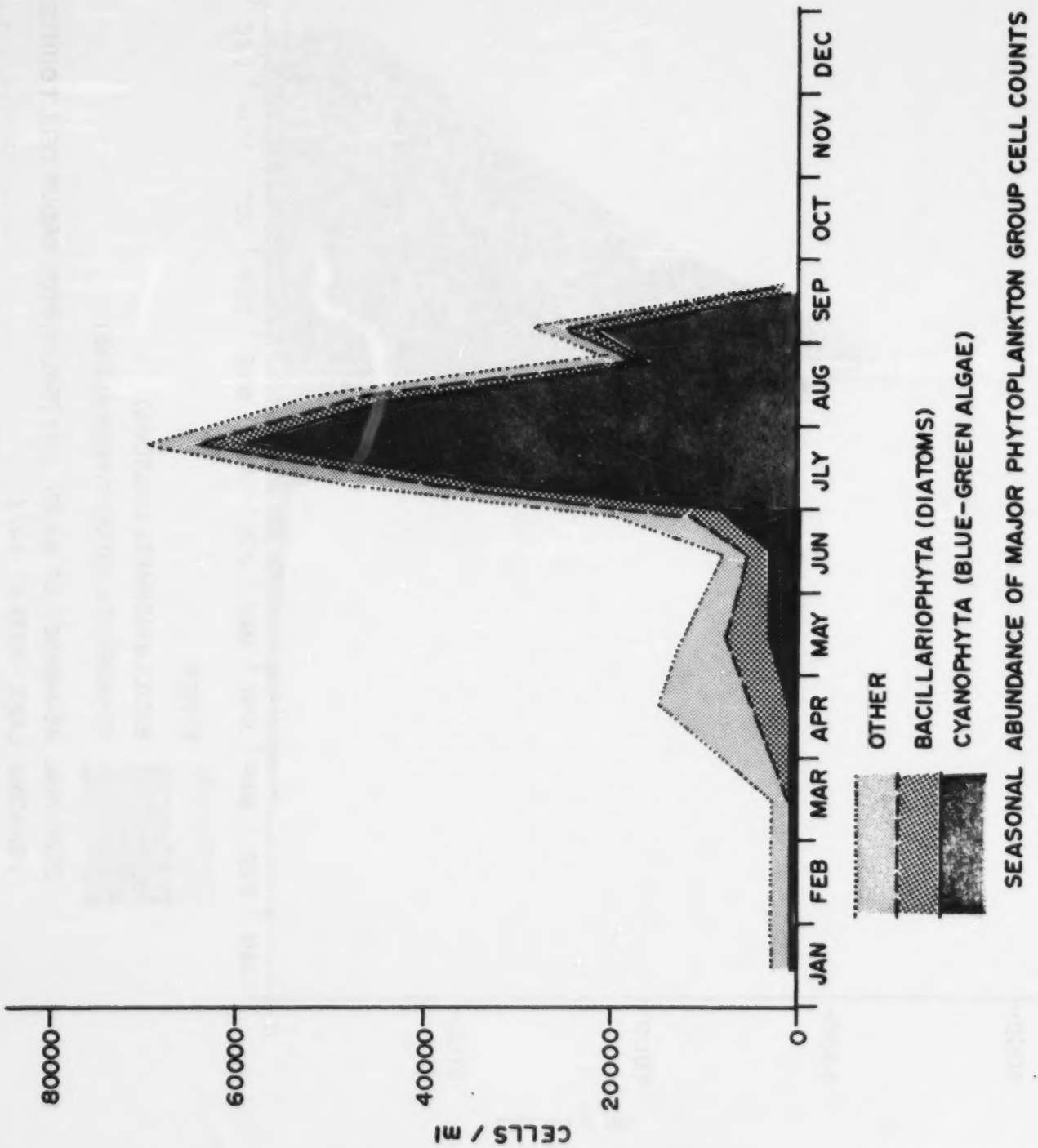


Figure 34. Occurrence and abundance of major phytoplankton taxa in Lake Johanna.

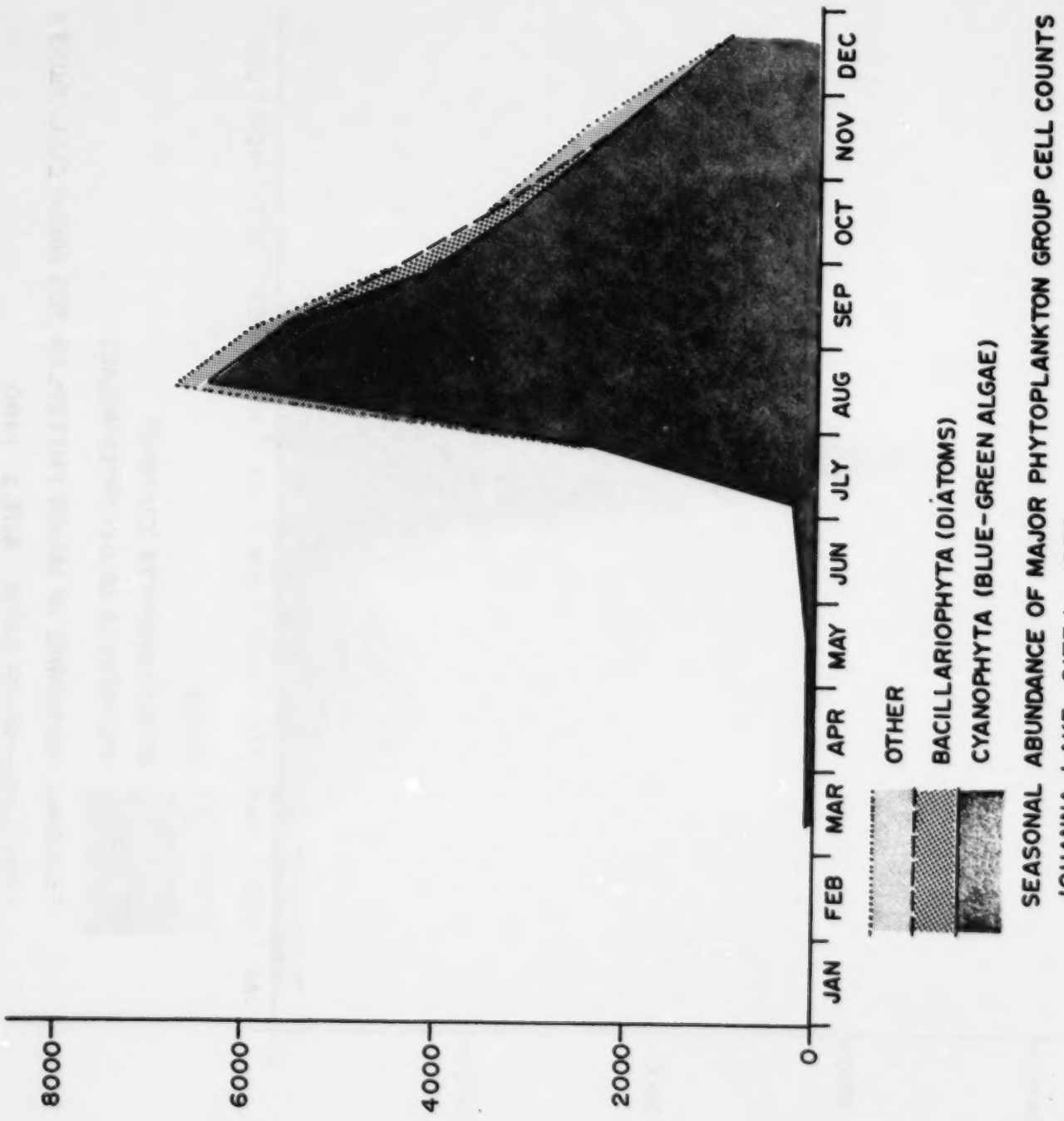


Figure 34. Occurrence and abundance of major phytoplankton taxa in Lake Johanna. (Continued)

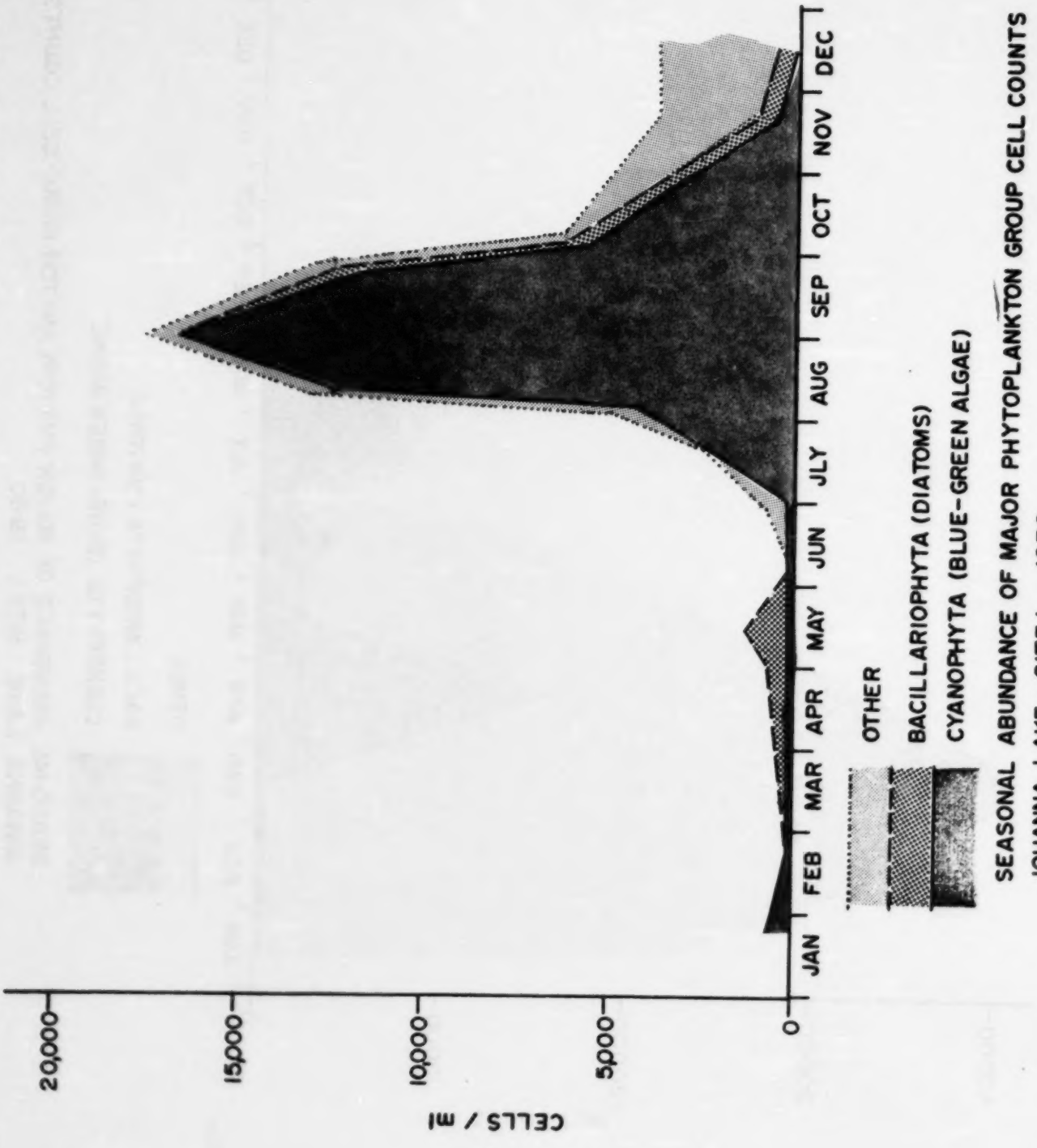
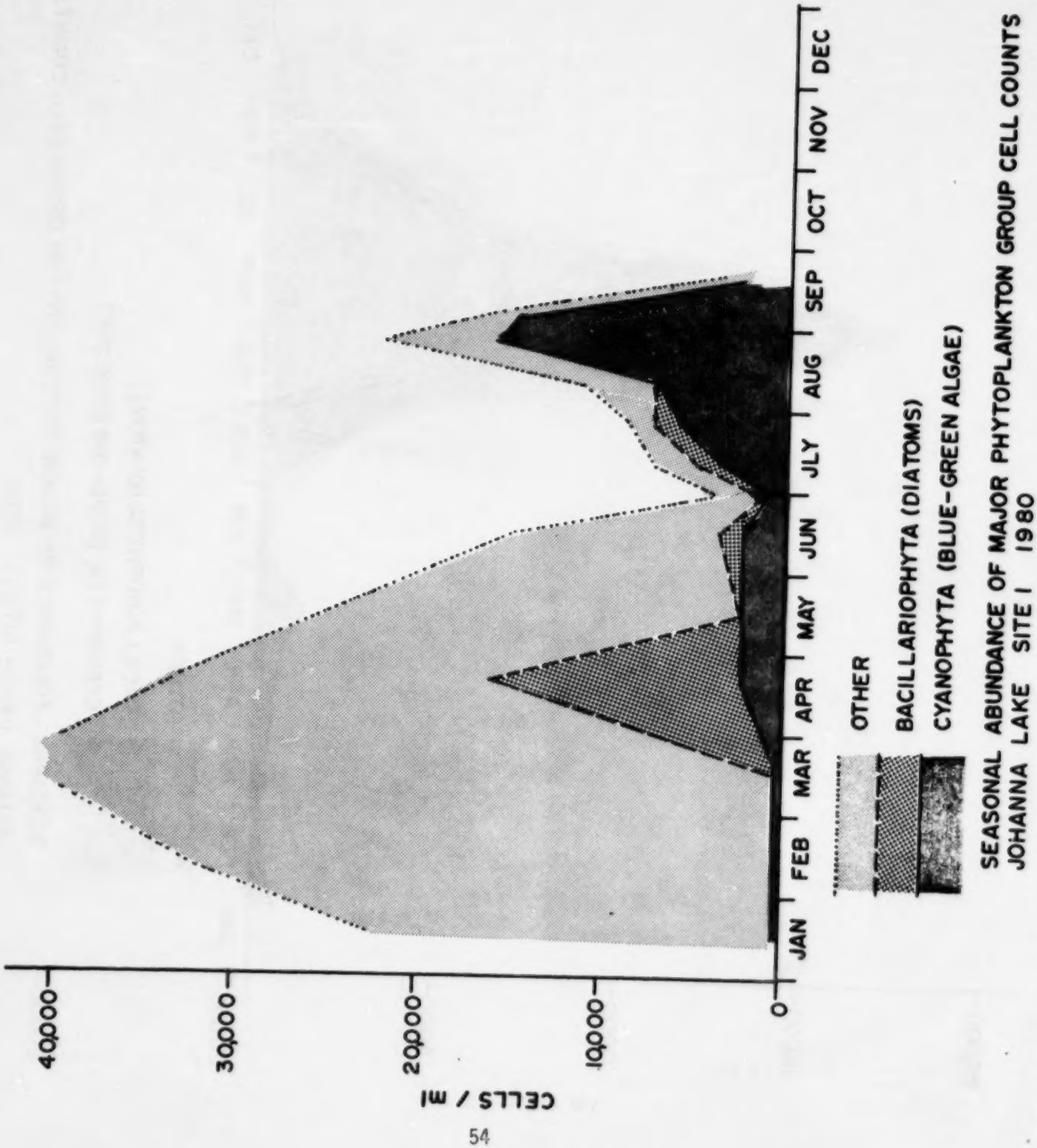


Figure 34. Occurrence and abundance of major phytoplankton taxa in Lake Johanna. (Continued)



The algal counts mirrored chlorophyll concentrations well in all years. In 1978 and 1979 blue-greens dominated in summer with Anabaena and Aphanizomenon in 1978 and with Phormidium and Anabaena in 1979 (Figure 35). Polycystis was noted for the first time in any of the lakes in late July and remained through September. In 1980 blue-greens were abundant during summer in the form of Chroococcus, but the green, Chlamydomonas, also remained abundant.

Phytoplankton analyses are tabulated for all the project lakes in Appendix C.

Macrophytes

Macrophytes were surveyed in Long Lake and in Lakes Johanna and Josephine in early August, 1978 and in mid-august, 1980. The purposes were (1) to establish baselines against which the effects of restoration could be measured and (2) to determine the extent to which nutrients were being pumped from the sediments into the lakewater by the plants. Plants were observed visually and by using a small hand rake. The survey was hampered by low transparency.

Long Lake

The situation was similar to that found by the DNR on July 10, 1929 - ". . . almost a complete absence of attached vegetation in the lake." The reasons seemed to be two - the bottom of the lake is hard with few areas of soft substrate in the littoral, and low transparency. It was found that 95 percent of the vegetation existed in less than one meter of wter and few plants were found at greater than 1 meter. Nuphar, a floating-leaved plant, grew to 1.3 meters depth. The emergents Typha and Scirpus were found in small beds in scattered clumps all along the shore but formed large beds only at the Rice Creek delta and in the bay north of the peninsula on the

Figure 35. Occurrence and abundance of major phytoplankton taxa in Lake Josephine.

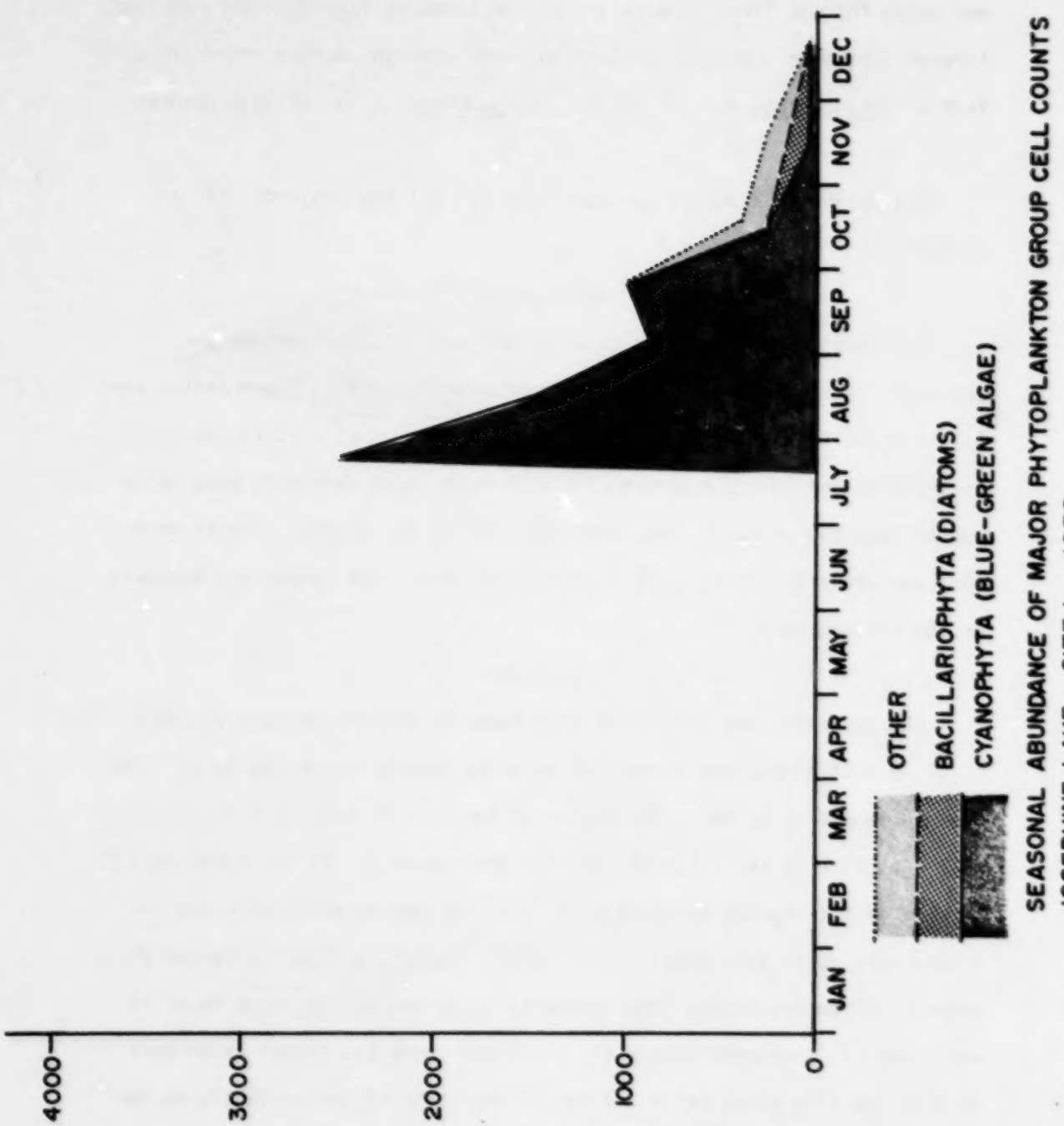


Figure 35. Occurrence and abundance of major phytoplankton taxa in Lake Josephine. (Continued)

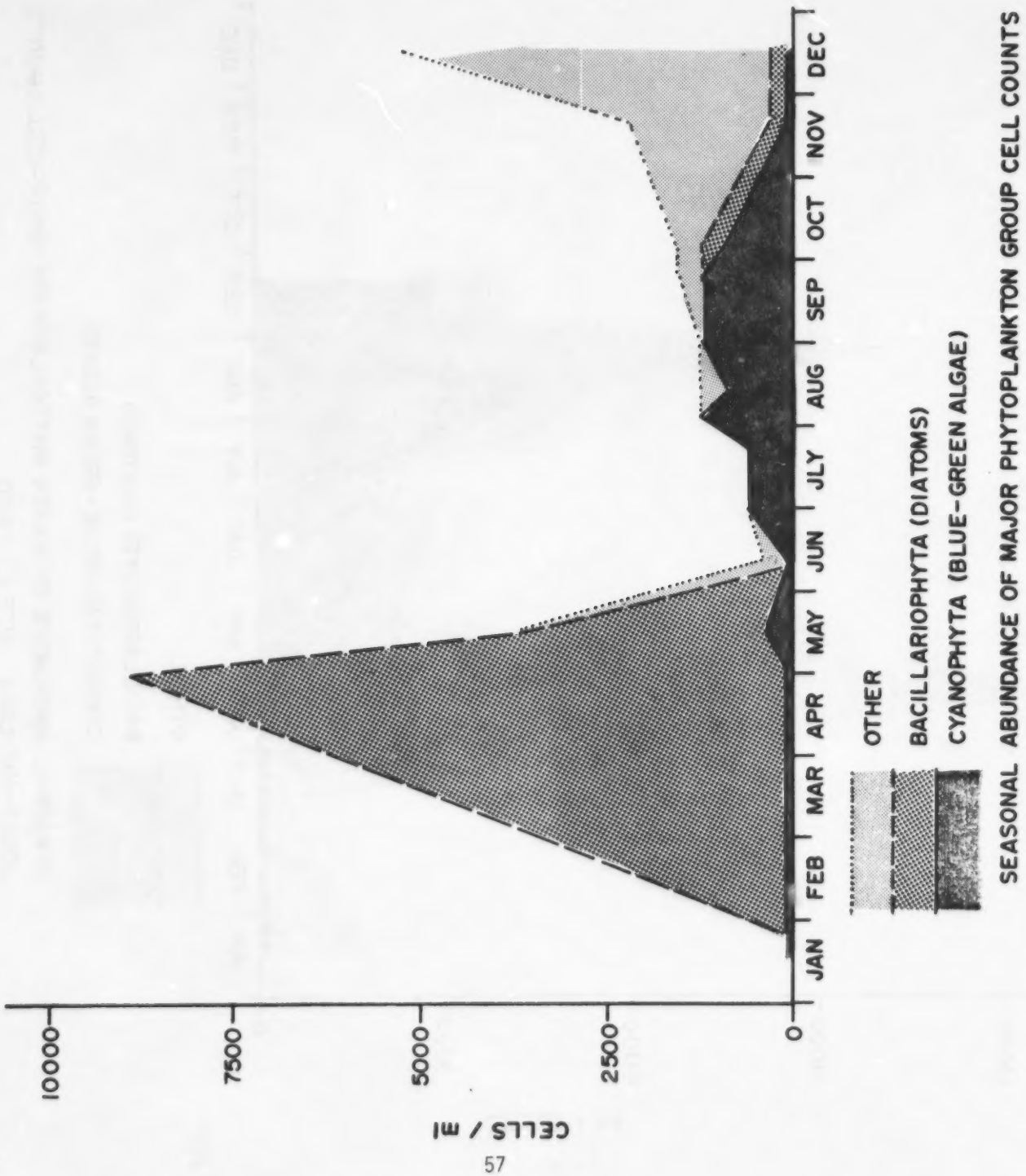
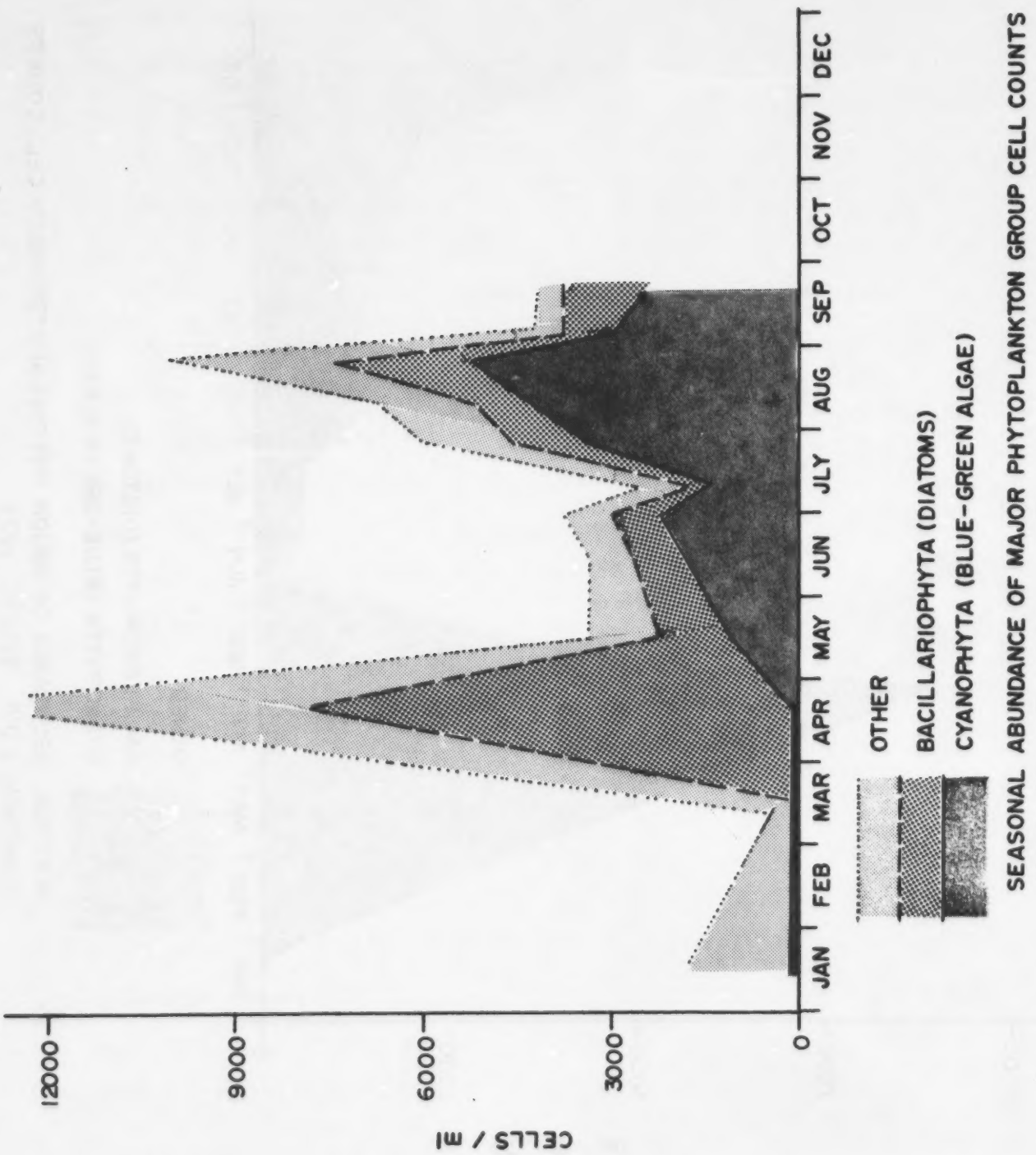


Figure 35. Occurrence and abundance of major phytoplankton taxa in Lake Josephine. (Continued)



west side. These two areas, covering about 2400 m^2, account for 95 percent of the emergents. The only floating-leaved forms were the small bed of Nuphar about 25 m^2 in an area on the west side. A few masses of free-floating Ceratophyllum were found on the lee side of the lake. The only two submerged forms found - Callitriche and Potamogeton pectinatus - were found near the Rice Creek Inlet and formed an area of less than 10 m^2 in extent. The second survey done in August, 1980, yielded very similar results but with somewhat greater area of submerged vegetation, namely Potamogeton crispus. Distributions on both dates are shown in Figure 36.

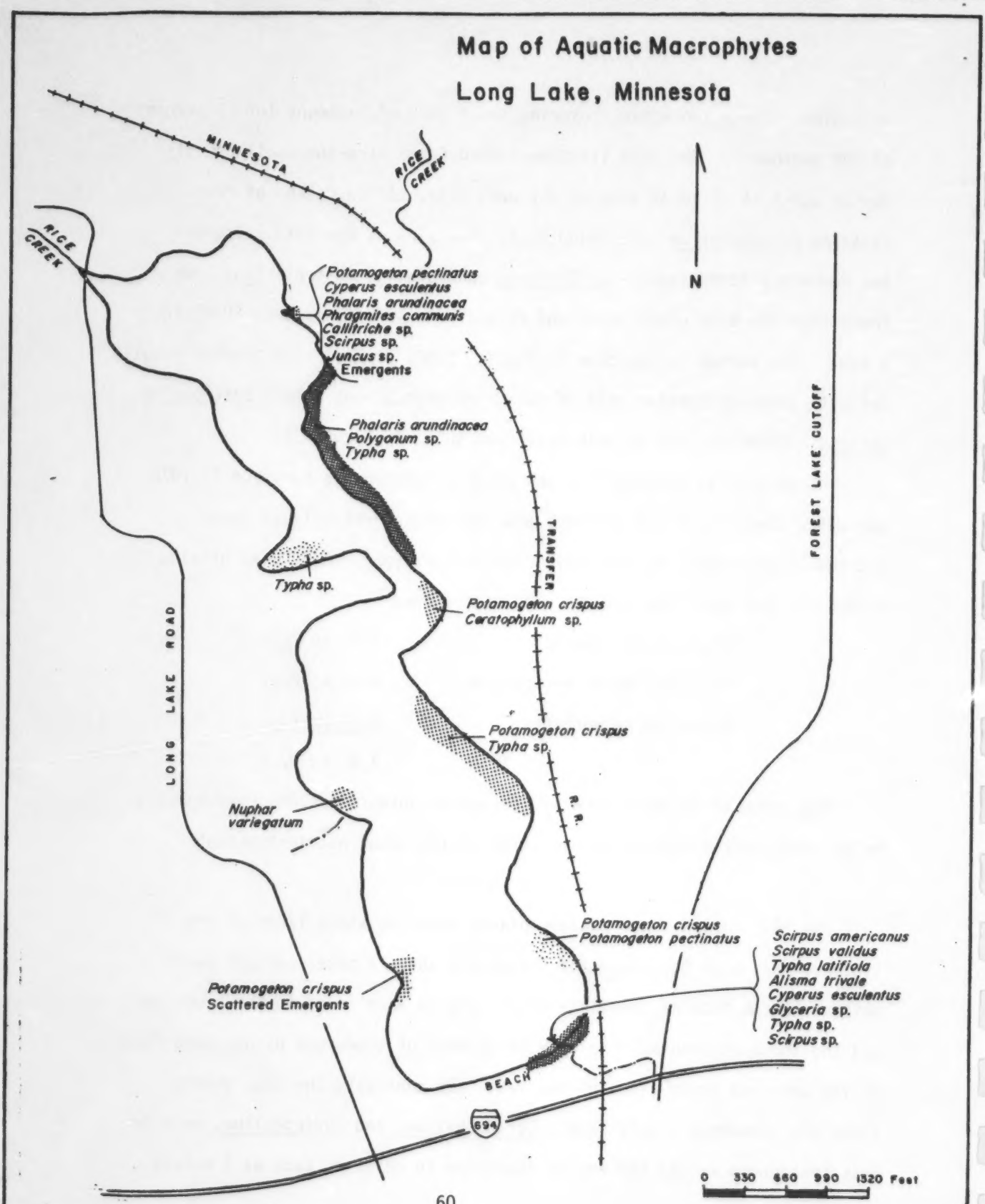
The phosphorus loading from the aquatic macrophytes surveyed in 1978 was calculated from plant coverage and from phosphorus release rates previously determined by Lie (1977) for Shagawa Lake. A 100-day growing season was assumed. The results were as follows:

Emergent macrophytes	7.7 kg P/yr
Floating-leaved macrophytes	0.08 kg P/yr
Submerged macrophytes	0.12 kg P/yr
TOTAL	7.9 kg P/yr

Thus release of phosphorus by the aquatic plants in Long Lake appears to be relatively insignificant in terms of the total nutrient budget.

Lake Johanna

The 1978 survey found aquatic plants covering about 1/6th of the littoral area with 80 percent of the plants above 1 meter and all above 2 meters. Large beds of floating-leaved species were found in the south bay and the south peninsula. The only large beds of submerged plants were found on the west and south sides of the lake. By contrast, the 1980 survey found the submerged plants Najas, Ceratophyllum, and Myriophyllum, more or less continuous around the entire shoreline in water as deep as 3 meters



SURVEY DATE: 8/13/80

Figure 36. Aquatic macrophyte distribution in Long Lake.

(Figure 37). Submergents were also more prominent around the island than in 1978. These findings indicate that the conditions for macrophyte growth are present in Lake Johanna and that the extent of growth may be largely a function of transparency in a given year.

Lake Josephine

This lake also had few macrophytes when surveyed in 1978 and when resurveyed in 1980, although a considerable amount of decaying unidentifiable vegetation was brought to the surface with grappling hooks in 1980. Again greater than 90 percent of the living plants were found in the first meter of depth with 1.5 meters being the deepest extent of growth. The 1980 survey found Potamogeton crispus in this lake as it had in Long Lake (Figure 38).

Zooplankton

Long Lake

Results of the zooplankton counts for Long Lake are shown in Tables 6 and 7. Approximately the same number of species of cladocerans and copepods occurred in both basins. However, there were some interesting differences and interrelationships. Daphnia pulex was present in 1978 occurring on only one date in the north basin but throughout the summer and fall in the south basin. It was not found in either basin in 1979 and 1980. Ceriodaphnia lacustris, abundant in both basins in 1979-1980, was rare in 1978. This reciprocal relationship with Daphnia pulex has been studied by Lynch (1979) and noted by others, (e.g. J. Shapiro, 1980). Interestingly while Ceriodaphnia was absent when Daphnia pulex was abundant, Diaphanosoma occurred only in the years with the D. pulex.

Daphnia retrocurva was rare with most Daphnia being D. galeata and D. parvula. Chydorus sphaericus was well represented throughout the years in

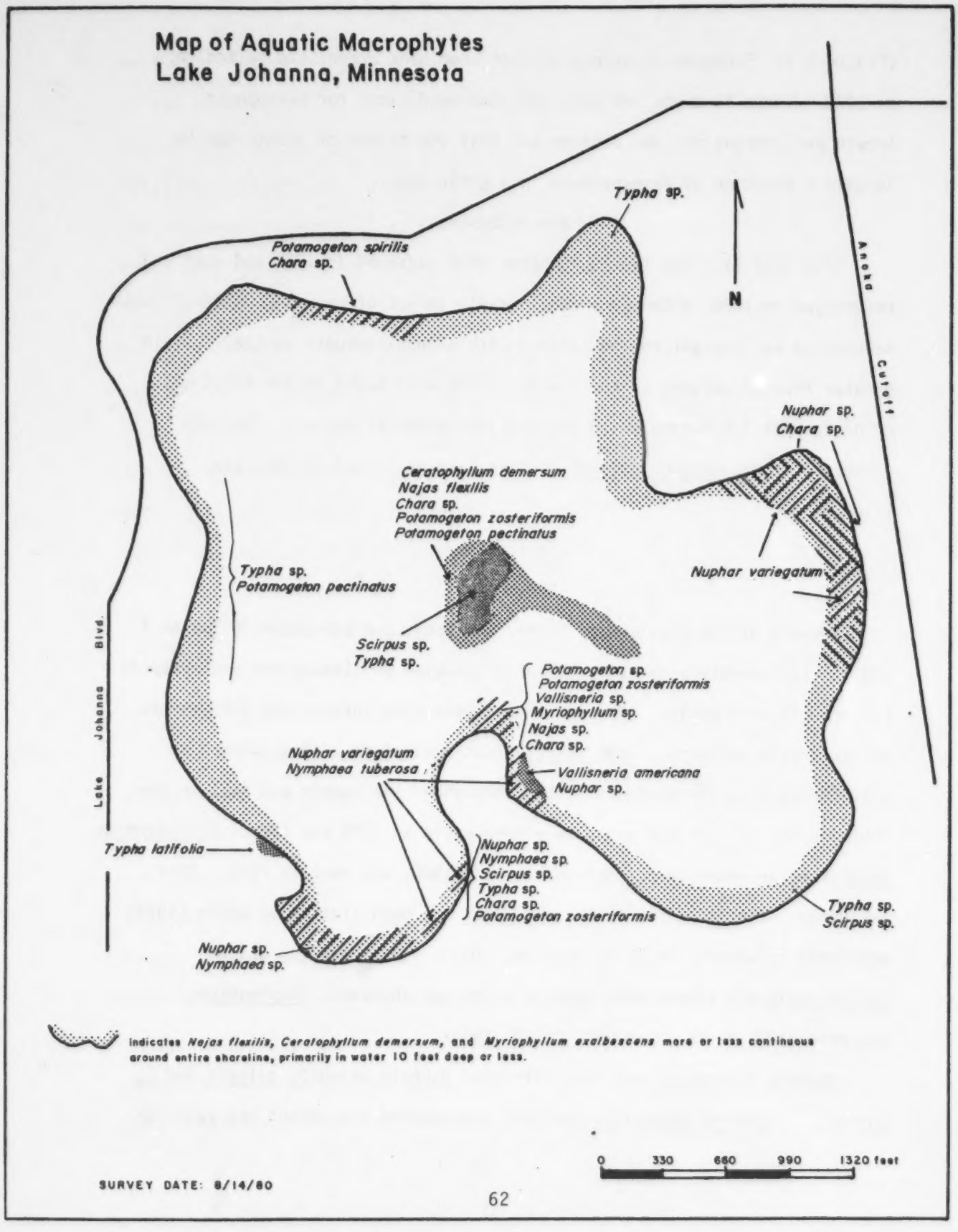


Figure 37. Aquatic macrophyte distribution in Lake Johanna.

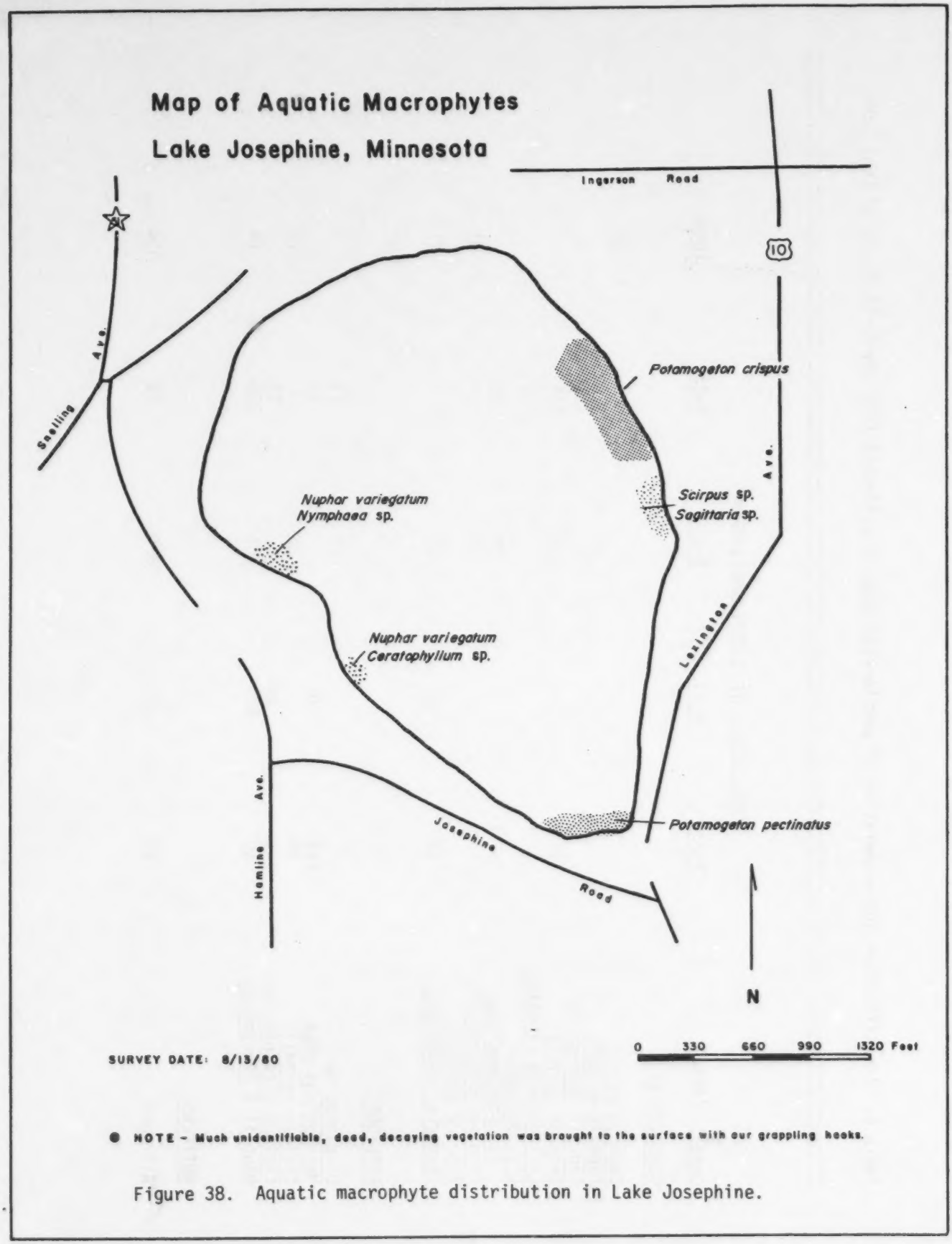


Figure 38. Aquatic macrophyte distribution in Lake Josephine.

Table 6. Identification and enumeration of zooplankton samples collected from the north basin of Long Lake.

	THOUSANDS OF ZOOPLANKTERS/M^2				
Date (1978)	7-27	8-17	9-6	9-25	10-16
CLADOCERANS					
Daphnia pulex					13
Daphnia galeata			63	30	
Daphnia retrocurva				6	
Daphnia parvula	95	276	138	114	
Ceriodaphnia lacustris				12	
Diaphanosoma leuchtenbergianum			25	18	
Bosmina longirostris			25	12	81
Bosmina coregoni					
Chydorus sphaericus	10	26	13		21
COPEPODS					
Diaptomus sp.			13	18	4
Mesocyclops edax	115	26		12	
Cyclops vernalis	19		25		21
Cyclops bicuspidatus		34		18	
Nauplii & Copepodids	10	181	201	138	64
ROTIFERS					
All taxa	10	268	829	72	554

Table 6. Identification and enumeration of zooplankton samples collected from the north basin of Long Lake. (Continued)

	THOUSANDS OF ZOOPLANKTERS/M^2								
Date (1979)	5-2	5-29	7-1	7-22	8-2	8-13	8-30	9-24	10-5
CLADOCERANS									
Daphnia pulex									
Daphnia galeata	38	68	51	67		86	175	95	241
Daphnia retrocurva									
Daphnia parvula		17		7		66	41	17	8
Ceriodaphnia lacustris		34	31	188		385	187	61	33
Diaphanosoma leuchtenbergianum									
Bosmina longirostris			41	161	159	1049	543	69	83
Bosmina coregoni			10					9	
Chydorus sphaericus		17		336		40		9	50
COPEPODS									
Diaptomus sp.	8	42	62	188	38	265	391	338	183
Mesocyclops edax				20					
Cyclops vernalis	30	1376		20			88		
Cyclops bicuspidatus		102	21		19	106		52	33
Nauplii & Copepodids	266	679	266	267	38	401	479	338	283
ROTIFERS									
All taxa	68	272	144	243	45	59	562	312	267

Table 6 Identification and enumeration of zooplankton samples collected from the north basin of Long Lake. (Continued)

THOUSANDS OF ZOOPLANKTERS/M^2

Date (1980)	4-22	5-20	6-16	6-30	7-13	7-28	8-11	8-25	9-8	9-22
CLADOCERANS										
Daphnia pulex										
Daphnia galeata		411	53	39	73	169	133	257	219	319
Daphnia retrocurva		200								
Daphnia parvula			35		17	78	124	58	89	247
Ceriodaphnia lacustris	111		21	25	221		527	128	111	
Diaphanosoma leuchtenbergianum										
Bosmina longirostris	513	308		35	173	226	659	443	422	597
Bosmina coregoni										
Chydorus sphaericus		77	39		376	113	49			239
COPEPODS										
Diaptomus sp.	226	72	42	43		22	181	62	102	163
Mesocyclops edax					28					
Cyclops vernalis		190	354		31			71	131	247
Cyclops bicuspidatus	354		92	142		52	133			
Nauplii & Copepodids	952	1694	542	78	304	69	593	341	302	443
ROTIFERS										
All taxa	442	713	287	61	176	95	97	421	592	705

Table 7. Identification and enumeration of zooplankton samples collected from the south basin of Long Lake.

	THOUSANDS OF ZOOPLANKTERS/M^2				
Date (1978)	7-27	8-27	9-6	9-29	10-16
CLADOCERANS					
Daphnia pulex	38	99	57	27	4
Daphnia galeata	48		126	332	122
Daphnia retrocurva					
Daphnia parvula		33	34	93	
Ceriodaphnia lacustris				9	
Diaphanosoma leuchtenbergianum		11	34	88	20
Bosmina longirostris	29	55	195	212	268
Bosmina coregoni					
Chydorus sphaericus	19		11		
COPEPODS					
Diaptomus sp.	67	132	322		169
Mesocyclops edax	10	11	11		4
Cyclops vernalis	10	11	23	80	28
Cyclops bicuspidatus		11		31	71
Nauplii & Copepodids	115	230	322	438	36
ROTIFERS					
All taxa	134	5603	1207	164	16

Table 7. Identification and enumeration of zooplankton samples collected from the south basin of Long Lake. (Continued)

THOUSANDS OF ZOOPLANKTERS/M^2

Date (1979)	5-2	5-20	6-18	7-1	7-27	8-2	8-13	8-30	9-24	10-8
CLADOCERANS										
Daphnia pulex										
Daphnia galeata	22	368		120	175		278	215	104	287
Daphnia retrocurva										
Daphnia parvula		28			94			113	35	
Ceriodaphnia lacustris				60	34		165	91	110	158
Diaphanosoma leuchtenbergianum										
Bosmina longirostris	11				141	48	390	725	245	358
Bosmina coregoni									24	
Chydorus sphaericus				9			35		104	201
COPEPODS										
Diaptomus sp.	22	35		172	397		399	374	311	201
Mesocyclops edax										
Cyclops vernalis	11	397			20			34		
Cyclops bicuspidatus			5	69	182	18	113		214	129
Nauplii & Copepodids	461	1161	8	155	444	6	509	272	217	745
ROTIFERS										
All taxa	11	21			666		113	222	307	301

Table 7. Identification and enumeration of zooplankton samples collected from the south basin of Long Lake. (Continued)

THOUSANDS OF ZOOPLANKTERS/M^2

Date (1980)	4-22	5-20	6-16	6-30	7-13	7-28	8-11	8-25	9-8	9-22
CLADOCERANS										
Daphnia pulex										
Daphnia galeata	223	177	257	159	156	100	297	273	5	107
Daphnia retrocurva		78								
Daphnia parvula		56	77		76	48		200	106	188
Ceriodaphnia lacustris	85		61	80	54		128	138		148
Diaphanosoma leuchtenbergianum										
Bosmina longirostris	276	124			149	82	62	745	170	209
Bosmina coregoni										
Chydorus sphaericus	143	151		21	36		35			
COPEPODS										
Diaptomus sp.	90	290	61	107	334		270	375		214
Mesocyclops edax										
Cyclops vernalis			383		36			57		199
Cyclops bicuspidatus	903	570		106	214	126	97			
Nauplii & Copepodids	589	479	904	106	468	208	677	403	239	437
ROTIFERS										
All taxa	133	91	32		454	199	125	326	138	641

both basins as expected from the presence of filamentous blue-green algae. Among the copepods the only clear pattern is for Mesocyclops edax which was present to a significant degree only in 1978.

Particular interest attaches to Daphnia as these herbivores have been shown to have the greatest effect on algal abundance (J. Shapiro, 1980). Taken as a whole there were no great differences in average concentrations of Daphnia between the north and south basins, and in fact even had there been some differences, it is unlikely whether this would have resulted in differences in algal abundances of the two basins. The reason is that the species present are generally small-bodied. Even the Daphnia pulex found in 1978 did not exceed 1.5 millimeters in length. As the filtering rate of Daphnia is a function of the cube of the body length, larger forms two millimeters or more in length are much more effective in reducing algal abundance. The presence of such small-bodied forms - even of the Daphnia pulex - may be explainable in Long Lake by fish predation. Two planktivorous fish, yellow perch and black crappie, are present in the lake, and by their predation on larger cladocerans are probably helping keep the remaining members of the population small in size. Only if these and other planktivores are reduced in number, or if a refuge for Daphnia exists where fish cannot follow or cannot feed, are the Daphnia likely to become a major force in controlling the algae in the lake.

Such a refuge may have been demonstrated in 1979. A special study on July 11th showed that the temperature profiles in Long Lake north and south were very similar, with stratification occuring in both, but with measurable dissolved oxygen extending to six meters in the south basin versus four meters in the north basin. Many more large-sized Daphnia were found below three meters in Long Lake south than in Long Lake north (Shapiro and Wright,

pers. comm.). As the south basin generally loses its hypolimnetic oxygen more slowly than the north, it is reasonable to expect that, all other things being equal, the larger species, Daphnia galeata, should predominate over such small species as Daphnia parvula in the south basin. This does seem to be the case.

Lakes Johanna & Josephine

Zooplankton counts for these two lakes are shown in Tables 8 and 9. As in the case of Long Lake, Daphnia pulex was absent in 1979 and 1980, but no data are available for 1978. The most surprising feature of the data in the tables is the relatively small abundance of Bosmina. Generally Bosmina is very abundant in the absence of large Daphnia, as it is in the north and south basins of Long Lake.

The data suggest moderately heavy fish predation in both of these lakes.

Hydrologic Budget

Long Lake

Hydrologic budgets were constructed for the north and south basins of Long Lake for the 1979 and 1980 water years. The components of those budgets are presented in Tables 10 - 13. Complete hydrologic data records for Long Lake are presented in Appendix D of this report.

The 1979 water year was wetter than normal. Annual precipitation totaled 32.80 inches compared to an average total of 28.37 inches. The 1980 water year recorded 27.51 inches of precipitation, slightly less than normal.

Mean hydraulic detention times were calculated for each lake basin for each water year. The calculated detention times for the north basin are 3.2 days and 20.0 days for the 1979 and 1980 water years, respectively. Corresponding detention times for the south basin are 23.98 days and 81.8

Table 8. Identification and enumeration of zooplankton samples collected from Lake Johanna.

	THOUSANDS OF ZOOPLANKTERS/M^2									
Date (1979)	5-2	5-20	6-14	7-1	7-22	8-6	8-13	8-30	9-24	10-8
CLADOCERANS										
Daphnia galeata	14	60	345	67	12	7	16	63	7	12
Daphnia retrocurva	-	-	35	78	37	14	16	25	7	6
Daphnia parvula	-	15	23	-	-	-	-	13	-	-
Ceriodaphnia lacustris	-	-	104	-	-	-	-	189	-	-
Diaphanosoma leuchtenbergianum	-	-	-	-	-	228	-	-	-	-
Bosmina longirostris	-	-	541	-	-	-	-	50	-	-
Chydorus sphaericus	14	-	12	-	12	41	109	-	-	-
COPEPODS										
Diaptomus sp.	-	60	173	212	379	152	179	101	159	155
Cyclops vernalis	580	3747	-	134	37	14	55	-	97	93
Cyclops bicuspidatus	-	1963	1369	-	-	-	-	-	-	-
Nauplii	1312	-	-	67	257	345	179	113	442	347
Copepodids	-	595	58	22	122	55	31	50	97	118
ROTIFERS										
Keratella valga	-	-	-	-	-	-	8	-	-	-
Kellicottia longispina	28	-	1243	11,931	1832	504	47	289	145	161
Brachionus calyciflorus	-	15	407	1015	-	-	-	-	-	-
Filinia longiseta	-	-	-	11	-	-	-	-	-	-
Keratella cochlearis	-	-	-	357	37	35	8	50	-	-
Trichocera multcrinis	-	-	-	112	183	28	-	-	-	-
Conchilus sp.	-	-	-	112	-	166	452	38	-	-
Asplanchna priodonta	-	-	-	-	24	-	-	-	-	6
Trichotria tetratis	-	-	-	-	-	7	31	-	14	-
Lecane sp.	-	-	-	-	-	35	-	-	-	-

Table 8. Identification and enumeration of zooplankton samples collected from Lake Johanna. (Continued)

THOUSANDS OF ZOOPLANKTERS/M^2

Date (1980)	4-21	5-20	6-17	7-1	7-13	7-28	8-11	8-25	9-8	9-22
CLADOCERANS										
Daphnia galeata	277	16	81	37	9	-	15	11	-	11
Daphnia retrocurva	-	-	12	42	13	8	11	5	7	11
Daphnia parvula	144	8	16	-	-	-	15	5	-	-
Ceriodaphnia lacustris	-	-	34	-	-	-	-	29	21	-
Diaphanosoma leuchtenbergianum	-	-	-	-	-	79	-	-	-	-
Bosmina longirostris	-	-	130	-	-	-	-	13	14	-
Chydorus sphaericus	33	-	9	-	9	20	58	-	-	-
COPEPODS										
Diaptomus sp.	166	43	53	56	121	74	73	19	25	115
Cyclops vernalis	1001	297	-	51	17	28	51	3	-	60
Cyclops bicuspidatus	-	283	322	-	-	-	-	-	-	-
Nauplii	349	-	9	33	95	110	22	11	12	164
Copepodids	-	116	34	14	48	20	76	8	14	60
ROTIFERS										
Conochilus sp.	-	-	-	-	-	116	181	53	16	-
Brachionus calyciflorus	-	5	121	423	-	-	-	-	-	-
Kellicottia longispina	-	-	369	520	707	317	25	11	69	110
Filinia longiseta	-	-	-	14	-	-	-	-	-	-
Trichocera multicrinis	-	-	-	56	9	23	-	-	-	-
Keratella cochlearis	-	-	-	112	13	31	15	8	14	-
Asplanchna priodonta	-	-	-	-	13	-	-	-	-	-
Trichotria tetratis	-	-	-	-	-	6	7	-	-	22

Table 9. Identification and enumeration of zooplankton samples collected from Lake Josephine.

	THOUSANDS OF ZOOPLANKTERS/M^2									
Date (1979)	5-2	5-20	6-14	7-1	7-22	8-6	8-13	8-30	9-24	10-8
CLADOCERANS										
Daphnia galeata	-	79	23	16	-		43	50	47	6
Daphnia retrocurva	-	-	-	22	60	-	43	238	140	12
Daphnia parvula	-	-	-	-	-	-	-	10	-	-
Bosmina longirostris	-	-	35	-	-	-	-	10	-	-
Chydorus sphaericus	-	-	12	65	542	-	116	80	545	-
COPEPODS										
Diaptomus sp.	-	-	94	86	84	-	73	248	312	150
Cyclops vernalis	127	2798	315	5	24	-	-	10	86	72
Nauplii	805	-	152	189	758	-	92	30	257	90
Copepodids	-	147	-	49	84	-	-	-	203	72
ROTIFERS										
Keratella cochlearis	12	589	280	378	48	0	0	50	234	138
Kellicottia longispina	-	91	304	7180	1408	-	415	466	28,814	602
Brachionus calyciflorus	-	11	35	22	-	-	-	-	-	-
Conchilus sp.	-	11	47	-	-	-	-	-	-	-
Trichotria tetractis	-	11	23	27	-	-	-	-	78	-
Asplanchna priodonta	-	-	35	-	48	-	-	-	-	-
Filinia longiseta	-	-	47	11	-	-	18	10	8	-
Trictcera sp.	-	-	-	-	-	-	6	-	-	-
Lecane sp.	-	-	-	-	-	-	-	80	-	-

Table 9. Identification and enumeration of zooplankton samples collected from Lake Josephine. (Continued)

	THOUSANDS OF ZOOPLANKTERS/M^2									
Date (1980)	4-21	5-20	6-17	7-1	7-13	7-28	8-11	8-25	9-8	9-22
CLADOCERANS										
Daphnia galeata	292	165	13	44	-	55	64	75	11	72
Daphnia retrocurva	146	-	-	58	68	23	60	274	14	142
Daphnia parvula	-	-	-	-	-	-	-	13	-	-
Ceriodaphnia lacustris	584	-	-	-	-	-	-	-	-	-
Bosmina longirostris	438	-	15	-	-	-	39	13	-	-
Chydorus sphaericus	151	-	8	127	450	12	85	106	-	473
COPEPODS										
Diaptomus sp.	312	-	38	170	64	-	37	173	-	366
Cyclops vernalis	292	64	105	15	34	6	28	22	-	110
Cyclops bicuspidatus	730	-	-	-	-	4	-	-	-	-
Nauplii	1606	175	51	200	77	21	48	44	21	128
Copepodids	1314	106	-	112	30	14	-	-	-	235
ROTIFERS										
Trichocera multierinis	-	-	-	-	-	14	53	-	-	-
Asplanchna priodonta	336	-	15	-	59	4	9	-	12	-
Keratella cochlearis	273	112	-	389	51	6	-	75	211	
Kellicottia longispina	234	85	80	4380	459	183	244	217	-	14,150
Conchilis sp.	-	101	-	-	-	-	-	-	-	-
Filinia longiseta	-	-	-	39	-	-	-	13	-	-
Brachionus calyciflorus	-	-	-	78	-	-	-	-	-	-
Trichotria tetractis	-	-	-	83	-	-	-	-	-	135
Lecane sp.	-	-	-	-	-	-	-	71	-	-

Table 10. Approximate hydrologic budget for Long Lake south basin, 1979 water year. (Units are acre-feet)

Component	Symbol	Annual Value
INFLOW TO LAKE		
Surface water	SI	4531.43
Precipitation	P	324.67
Net groundwater change	ΔGW	2770.31
Total		7626.41
OUTFLOW FROM LAKE		
Surface water	SO	7432.91
Evaporation	E	269.38
Change in lake storage	ΔS	-75.88
Total		7626.41
Total inflow minus total outflow		0

θ = 23.98 days

Table 11. Approximate hydrologic budget for Long Lake north basin, 1979 water year. (Units are acre-feet)

Component	Symbol	Annual Value
INFLOW TO LAKE		
Surface water	SI	54796.43
Precipitation	P	167.26
Net groundwater change	ΔGW	1362.46
Total		56326.15
OUTFLOW FROM LAKE		
Surface water	SO	56220.11
Evaporation	E	134.68
Change in lake storage	ΔS	-28.64
Total		56326.15
Total inflow minus total outflow		0

θ = 3.2 days

Table 12. Approximate hydrologic budget for Long Lake south basin, 1980 water year. (Units are acre-feet)

Component	Symbol	Annual Value
INFLOW TO LAKE		
Surface water	SI	3588.30
Precipitation	P	272.21
Net groundwater change	ΔGW	5233.77
Total		9094.28
OUTFLOW FROM LAKE		
Surface water	SO	8712.84
Evaporation	E	307.98
Change in lake storage	ΔS	73.46
Total		9094.28
Total inflow minus total outflow		0

θ = 81.8 days

Table 13. Approximate hydrologic budget for Long Lake north basin, 1980 water year. (Units are acre-feet)

Component	Symbol	Annual Value
INFLOW TO LAKE		
Surface water	SI	33187.49
Precipitation	P	140.24
Net groundwater change	ΔGW	2573.29
Total		35901.02
OUTFLOW FROM LAKE		
Surface water	SO	35719.33
Evaporation	E	153.99
Change in lake storage	ΔS	27.70
Total		35901.02
Total inflow minus total outflow		0

θ = 20.0 days

days. Normalized to an average water year, the mean hydraulic residence times for the north and south basins of Long Lake were calculated to be 12 days and 54 days, respectively.

The hydrologic budgets indicate that there is a net influx of groundwater into the lake basins. Groundwater contribution to the south basin is of similar magnitude to surface water inflows. In 1979 groundwater contributed 2770 acre-feet of water compared to 4531 acre-feet of surface inflows. During 1980 the groundwater influx to the south basin was 5234 acre-feet exceeding the 3588 acre-feet of surface inflow. Groundwater influx to the north basin of Long Lake is significant, but of smaller relative importance than in the south basin. In 1979, 1326 acre-feet of groundwater entered the north basin as compared to 54,796 acre-feet of surface water inflow. The influx of groundwater to the north basin is similar to that entering the south basin, but a much smaller percentage of the total annual inflow (2.4 percent versus 36.3 percent). Similarly, in 1980 the groundwater entering the north basin of Long Lake was significant, 2573 acre-feet, but a relatively small percentage of the total inflow volume (7.2 percent). Surface inflows were 33,187 acre-feet for the north basin during the 1980 water year.

The significant feature of the calculated hydrologic budgets is the short hydraulic detention periods. The rapid turnover of waters in each basin will dictate the time required for the lake to come to a new equilibrium state following any change in phosphorus loadings. Such times to equilibration would be short.

The hydrologic budgets indicate that the north basin is dominated by the flow of Rice Creek. The water quality of the north basin is largely controlled, therefore, by the quality of Rice Creek waters, and is not well

buffered against changes in influent water quality. The water quality of the south basin of Long Lake is better buffered against such water quality variations.

Total Phosphorus Loadings

Long Lake

Total external phosphorus loadings were calculated for both basins of Long Lake as shown in Tables 14 and 15. Annual phosphorus loads to the south basin for 1979 and 1980 water years were 1003 kg and 999 kg. Corresponding loads to the north basin were 9329 kg and 10,201 kg, respectively. Phosphorus loading data are summarized in Appendix D of this report.

Normalized to an average water year and expressed on an areal basis, the annual loading rates are 360 kg/ha and 21.8 kg/ha for the north and south basins of Long Lake, respectively. Again, the influence of the inflow of Rice Creek into the north basin of Long Lake can be seen. The phosphorus loading rate of the north basin is 16.5 times that of the south basin. Phosphorus loads were remarkably similar in both years of record for both lake basins, despite significantly different annual hydrologic budgets.

Since both 1979 and 1980 water years passed without any major lake restoration work being completed, both years represent pre-treatment conditions. Thus the data provide a base against which post-treatment water quality can be compared. Following construction of watershed improvements designed to reduce sediment and nutrient export to Long Lake, nutrient loadings may be compared to the data reported here. The efficacy of the watershed improvements can then be judged. Present loading rates are extremely high by any criterion and significant reductions will have to be effected to result in significantly improved water quality.

Table 14. Approximate total phosphorus loadings to Long Lake north basin, 1979 and 1980 water years. (Units are kg P).

Component	Annual Value
1979 Water Year	
Surface water inflow.	9281.96
Atmospheric (precipitation & dry fallout)	13.81
Groundwater inflow.	33.61
Total	9329.38
1980 Water Year	
Surface water inflow.	10123.27
Atmospheric (precipitation & dry fallout)	13.81
Groundwater inflow.	63.47
Total	10200.55

Table 15. Approximate total phosphorus loadings to Long Lake south basin, 1979 and 1980 water years. (Units are kg P).

Component	Annual Value
1979 Water Year	
Surface water inflow.	907.80
Atmospheric (precipitation & dry fallout)	27.15
Groundwater inflow.	68.34
Total	1003.29
1980 Water Year	
Surface water inflow.	842.30
Atmospheric (precipitation & dry fallout)	27.15
Groundwater inflow.	129.11
Total	998.56

Based on the Dillon and Rigler (1974) model, an acceptable areal loading rate for the north basin of Long Lake is 23.0 kg/ha annually. Loadings greater than 45.9 kg/ha are considered excessive. Current loading, as previously stated, averages 360 kg/ha. For the south basin, acceptable, excessive and current average loading rates are 3.6, 8.3 and 21.8 kg/ha, respectively. Clearly, the north basin loading must be reduced by an order of magnitude to result in good water quality. A similar reduction in south basin loading is required. Lesser reductions in phosphorus loading will improve water quality but will not remove the lake from its eutrophic classification.

Internal phosphorus loads to the two basins of Long Lake have not been factored into the foregoing load calculations. The annual internal loads were calculated to be 905 and 285 kg for the north and south basins, respectively. These additional phosphorus loads are exerted during summer periods of hypolimnetic anoxia. To the extent that the internal load is available for algal growth, it reaches the algae at the height of its growing season, contributing to bloom conditions.

Sediment Phosphorus Release Experiments

The results of sediment phosphorus release experiements showed that release rates for sediments of the two Long Lake basins were very different. The data in Table 16 represent the concentrations of ortho-phosphate phosphorus in the experimental microcosms. Those concentration data were converted to mass of phosphorus in the water overlying the microcosm sediments (Table 17) plotted in Figures 39 and 40. Aerobic phosphorus release was not detectable for sediments from both the north and south basins of Long Lake. On an areal basis, anaerobic phosphorus release rates were 7.7 mg/m^2 day and 22.0 mg/m^2 day for the north and south basins, respectively.

Table 16. Results of Long Lake sediment phosphorus release experiments; ortho-phosphate phosphorus concentrations of water overlying sediments.

Days of Incubation	Water Volume (Liters)	Ortho-phosphate Phosphorus Concentrations (mg/L) North Basin Aerobic	North Basin Anaerobic	South Basin Aerobic	South Basin Anaerobic
1	3.243	.011	.007	.010	.025
2	3.192	.008	.007	.011	.032
3	3.140	.007	.007	.013	.039
4	3.089	.006	.008	.013	.046
5	3.037	.005	.015	.012	.056
6	2.986	.004	.026	.010	.097
7	2.935	.006	.030	.008	.144
8	2.882	.007	.036	.008	.207
9	2.832	.007	.040	.010	.302
10	2.779	.006	.051	.008	.274
11	2.728	.005	.069	.008	.520
12	2.676	.006	.110	.012	.570
13	2.625	.006	.120	.022	.710
14	2.574	.009	.220	.013	.790
15	2.522	.009	.234	.017	.820
16	2.471	.008	.234	.005	.880
17	2.419	.008	.282	.005	.875
18	--	--	--	--	--
19	--	--	--	--	--
20	2.368	--	--	.007	1.055
South basin columns spiked with 1 liter of 5 mg/L phosphate Phosphorus solution. (3/10/80)					
21	3.317	--	--	3.080	3.045
22	3.266	--	--	2.541	2.904
23	3.215	--	--	2.189	2.816
24	3.164	--	--	1.826	3.344
25	3.114	--	--	1.452	3.036
26	3.063	--	--	1.177	2.607
27	3.012	--	--	1.298	2.992
South basin anaerobic column switched to aerobic.					
				Aerobic	Aerobic
28	2.961	--	--	1.056	2.200
29	2.910	--	--	1.023	2.189
30	2.859	--	--	.825	1.903
31	2.808	--	--	.770	1.705

Table 17. Results of Long Lake sediment phosphorus release experiments; mass of ortho-phosphate phosphorus of water overlying sediments.

Days of Incubation	Ortho-phosphate Phosphorus mass (mg) North Basin Aerobic	North Basin Anaerobic	South Basin Aerobic	South Basin Anaerobic
1	.036	.023	.032	.081
2	.026	.022	.035	.102
3	.022	.022	.041	.122
4	.019	.025	.040	.142
5	.015	.046	.036	.170
6	.012	.078	.030	.290
7	.018	.088	.023	.423
8	.020	.104	.023	.597
9	.020	.113	.028	.855
10	.017	.142	.022	1.039
11	.014	.188	.022	1.419
12	.016	.294	.032	1.525
13	.016	.315	.058	1.864
14	.023	.566	.033	2.033
15	.023	.590	.043	2.068
16	.020	.578	.012	2.174
17	.019	.682	.012	2.117
18	--	--	--	--
19	--	--	--	--
20	--	--	.017	2.498
South basin columns spiked with 1 liter of 5 mg/L phosphate phosphorus solution (3/10/80).				
21	--	--	10.216	10.100
22	--	--	8.299	9.484
23	--	--	7.038	9.053
24	--	--	5.777	10.580
25	--	--	4.522	9.454
26	--	--	3.605	7.985
27	--	--	3.910	9.012
South basin anaerobic column switched to aerobic.				
			Aerobic	Aerobic
28	--	--	3.127	6.514
29	--	--	2.977	6.370
30	--	--	2.359	5.441
31	--	--	2.162	4.788

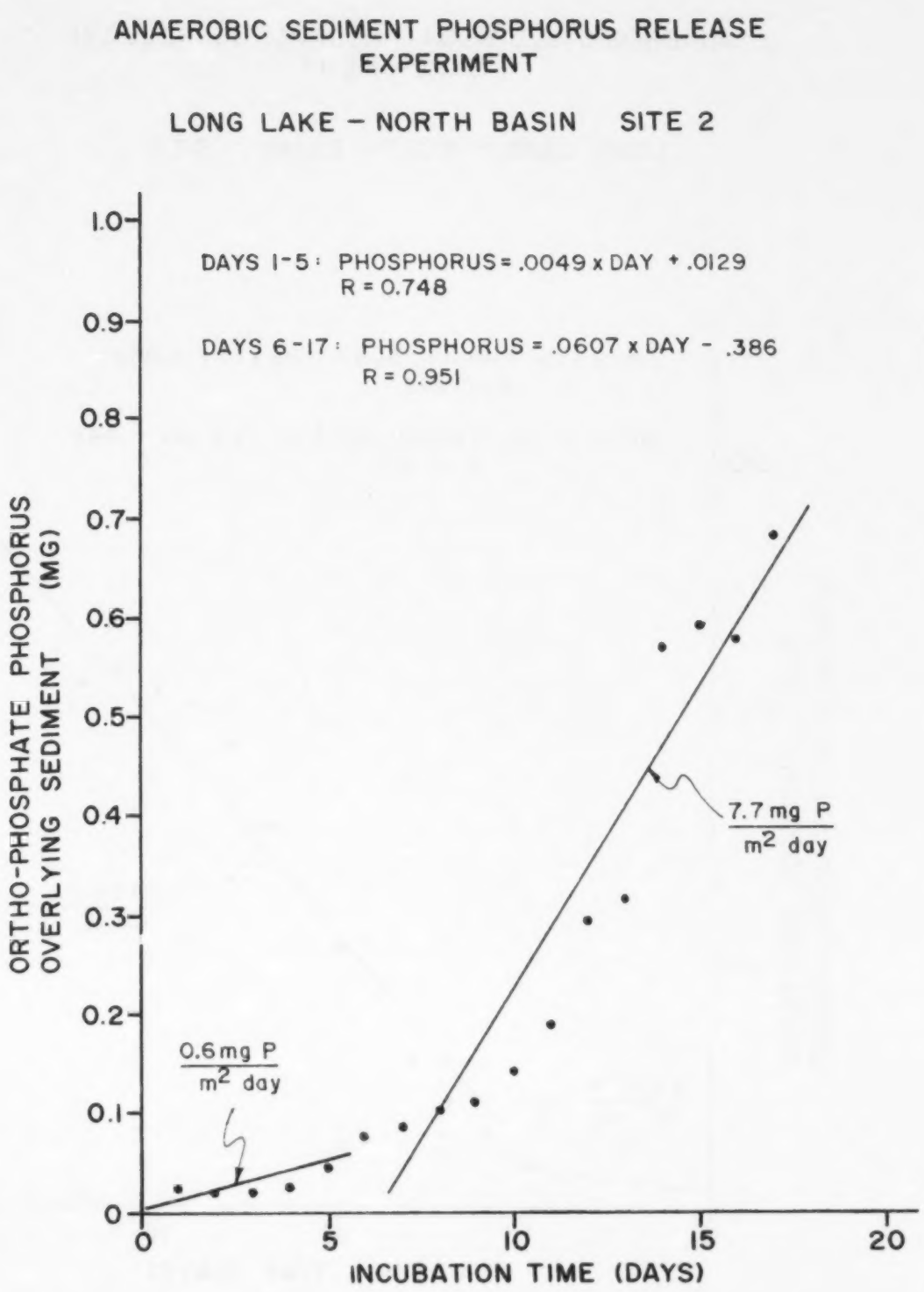


Figure 39. Anaerobic phosphorus release from the sediment of the north basin of Long Lake.

ANAEROBIC SEDIMENT PHOSPHORUS RELEASE EXPERIMENT

LONG LAKE – SOUTH BASIN SITE 5

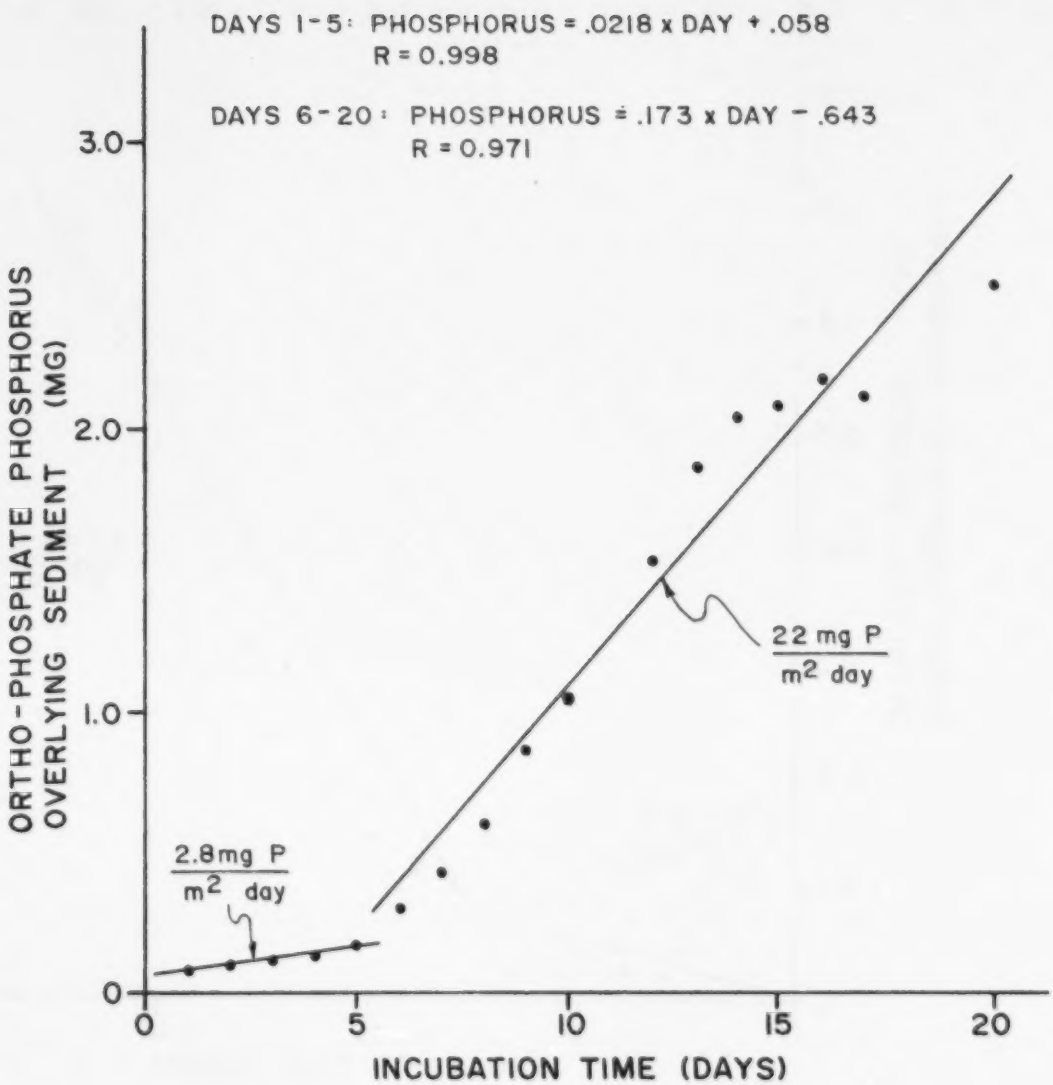


Figure 40. Anaerobic phosphorus release from the sediment of the south basin of Long Lake.

Anaerobic phosphorus release rates were calculated from data collected after five days of incubation. Data from the first five days of the experiment exhibited a much lower rate of phosphorus release. Those lesser phosphorus release rates were calculated to be 0.6 mg/m^2 day and 2.8 mg/m^2 day for the north and south basins of Long Lake respectively. The release rates over the first five days of the experiment are characteristic of declining dissolved oxygen concentrations and falling redox potential. As redox falls, phosphorus is initially released slowly and then more rapidly as ferric iron is converted to ferrous iron.

The rate of sediment phosphorus release in the north basin on Long Lake is only 40 percent that of the south basin. This fact is probably due to a higher amount of clastic material in the north basin sediments attributable to the inflow of Rice Creek. The results of this experiment have implications for the nutrient budgets of the two Long Lake basins. If these rates are applied to the area of anoxic water over the periods of anoxia, a significant internal phosphorus load could be realized.

Assuming that the rates apply to 90 days annually over areas equivalent to half the surface areas of the two lake basins, internal phosphorus loads to the north and south basins are 85 kg and 480 kg, respectively. The foregoing assumptions are generally consistent with profile water chemistry data observed at Long Lake during this study. Release rates calculated from data collected after at least six days of incubation were used to estimate internal loads since stratification and hypolimnetic anoxia were generally continuous. In lakes where stratification and hypolimnetic anoxia are ephermeral, the lower initial phosphorus release rates would be more properly used to estimate internal loading. Winter periods of anoxia have not been included in the internal load calculations since they do not influence

summer phytoplankton populations. The rapid flushing of both basins mitigates the possibility of any such influences.

Enrichment (Bioassay) Experiments

The enrichment experiments indicated that there were not clear-cut limiting nutrients in either the north or the south basins of Long Lake. Nutrient limitations varied throughout the summer seasons and annually. Table 18 summarizes the results of the enrichment experiments. The apparent limiting nutrient, nitrogen or phosphorus, is indicated. The results of the 13 July 1979 enrichment experiment are presented in Figures 41 and 42 to demonstrate how results were interpreted.

During 1978, nitrogen appeared to limit phytoplankton growth in the north basin of Long Lake. The south basin showed phosphorus, or phosphorus in combination with nitrogen, to be limiting. Since the north basin of the lake is heavily influenced by the flow of Rice Creek and since high levels of phosphorus were observed to be present in Rice Creek waters, phosphorus did not seem to be in short supply and thus probably not limiting. As discussed in the section of this report regarding phosphorus loadings, the annual phosphorus load to the north basin is approximately 59.0 kg/ha annually. The corresponding value for the south basin is only approximately 3.6 kg/ha. The difference in areal loading rates is greater than 16 fold. This supports the observation that the north basin is less limited by phosphorus than is the south basin.

The year 1978 was a relatively wet one and streamflows were correspondingly high. The year 1979, however, was drier and streamflows were less. In 1979, nitrogen seemed to be limiting in the south basin of Long Lake, often in combination with phosphorus. At the same time, the combination of nitrogen and phosphorus seemed to control phytoplankton in the north basin.

Table 18. Results of Long Lake enrichment (bioassay) experiments. Response of cultures to enrichments are expressed as percentages of the control culture after the indicated period of incubation.

Lake Basin	Starting Date	Days of Incubation	Enrichment* P	N	N + P	Si	TM	All	Indicated Limiting Factor
North	7/28/78	5	91.8	291.5	87.4	94.4	93.1	301.6	Nitrogen
	8/18/78	5	95.5	350.2	348.3	99.4	88.2	312.4	Nitrogen
	9/7/78	5	105.0	238.1	252.7	98.7	76.4	81.5	Nitrogen
	7/13/78	10	99.0	160.7	221.6	97.4	111.2	386.1	Nitrogen & Phosphorus
	7/24/79	8	101.5	101.2	176.2	65.9	53.5	114.8	Nitrogen & Phosphorus
	8/4/79	6	163.8	118.8	328.2	90.6	60.4	183.2	Nitrogen & Phosphorus
	8/14/79	16	186.5	276.3	286.6	124.6	180.4	591.0	Nitrogen & Phosphorus
South	7/28/78	7	111.3	188.7	194.1	85.7	115.3	30.0	Nitrogen & Phosphorus
	8/18/78	7	169.5	147.1	318.4	165.5	80.5	210.3	Nitrogen & Phosphorus
	9/7/78	5	153.4	98.5	140.0	97.9	15.6	16.8	Phosphorus
	7/13/79	5	99.5	243.3	225.5	97.1	84.2	150.0	Nitrogen
	7/24/79	4	91.9	174.7	236.3	90.1	63.0	131.8	Nitrogen
	8/4/79	6	152.8	72.1	81.9	104.0	83.0	95.8	Phosphorus
	8/14/79	16	153.2	135.1	167.8	98.0	60.0	255.1	Nitrogen & Phosphorus

*P = 50 µg/l PO_4 - P

N = 300 µg/l NO_3/NH_3 - N

N + P = NO_3/NH_3 -N + PO_4 - P

Si = 2 mg/l SiO_2

TM = 1 ml trace metal solution

All= All additions

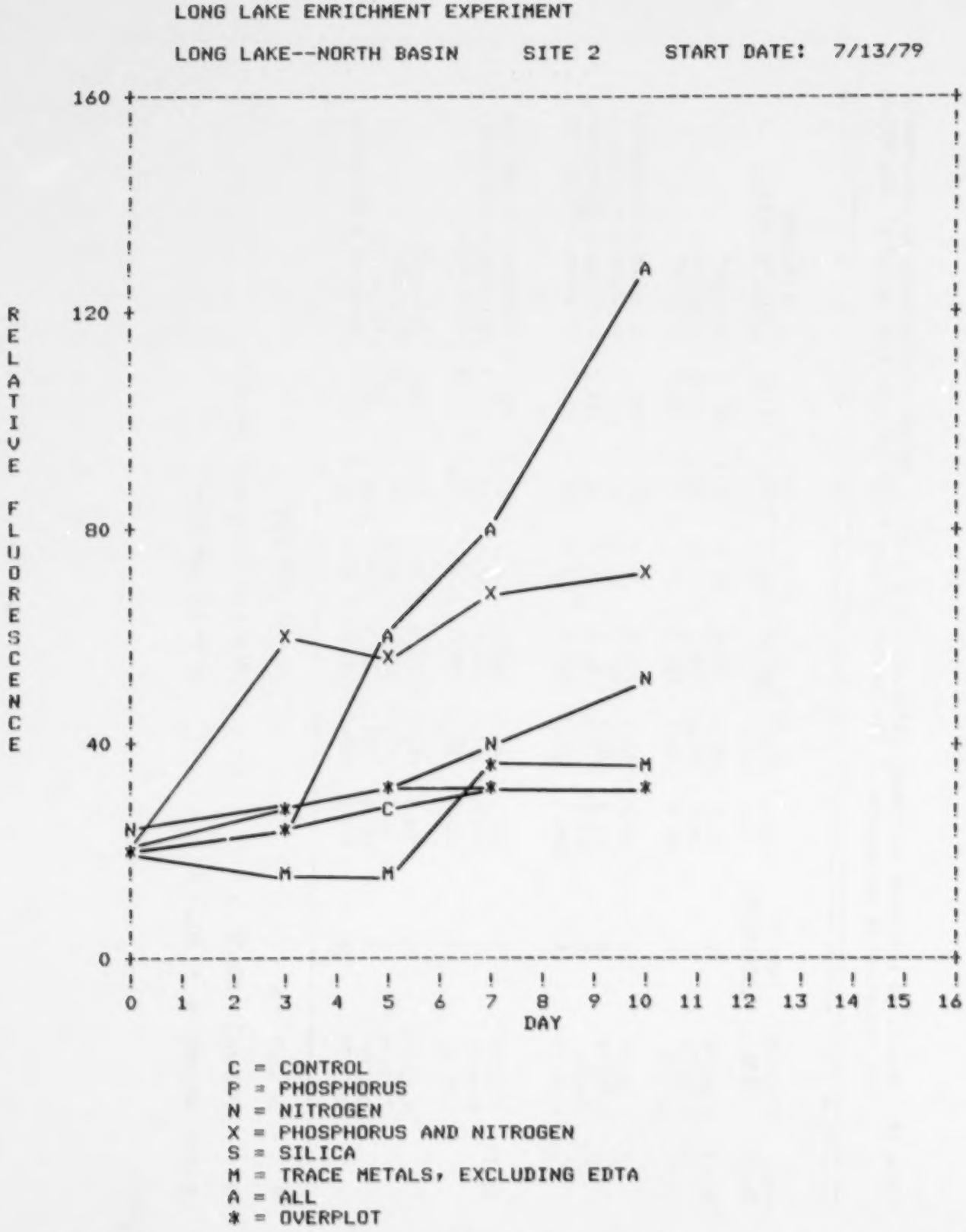


Figure 41. Growth of north basin Long Lake phytoplankton in response to various nutrient additions. 11/10/79

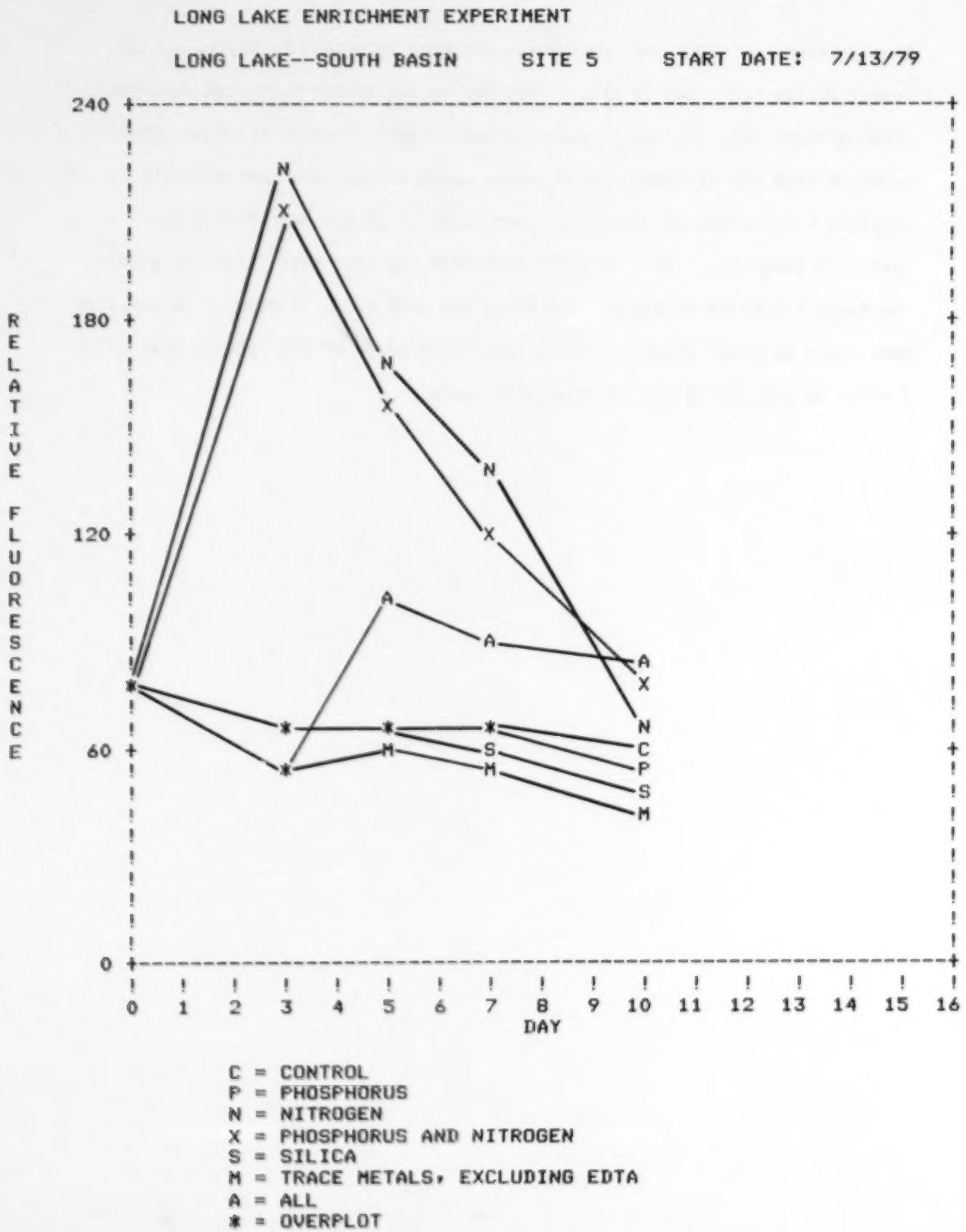


Figure 42. Growth of south basin Long Lake phytoplankton in response to various nutrient additions. 11/10/79

This pattern indicates that phosphorus was more important to phytoplankton growth during 1979 than in 1978. That may be due to the fact that phosphorus loadings were less the second year because of variations in climate. The evidence from the enrichment experiments seems to indicate that multiple nutrient limitations are the best interpretation of the data from both basins of Long Lake. This is consistent with the fact that TN/TP are within the range for which multiple limitations are indicated. A general observation that could be made, however, is that the north basin of the lake is less limited by phosphorus than is the south basin.

SUMMARY

Probable Lake Response to Restoration Measures

Long Lake

Since no significant lake restoration measures were completed during the term of this evaluation study, no report on response can be made. However, speculation may be made about the probable response of the lake to reductions in phosphorus loading. Such speculation is based on the results of monitoring during the three years of study.

Two years of hydrologic and nutrient loading data were collected during this study. Insufficient data are available to construct a good chlorophyll/P loading model for the two basins of Long Lake. A good relationship between chlorophyll a and total phosphorus concentrations can, however, be used to speculate about the response of lake water quality to a reduction in phosphorus loading.

The Dillon and Rigler (1974) model of phosphorus concentration in lake water equates phosphorus concentration to an expression as follows:

$$P_{spring} = \frac{L\ (1-R_{exp})}{\bar{z}\ \rho}$$

where P_{spring} is the concentration in mg/l of total phosphorus in the water at spring overturn, L is the phosphorus loading in $gm^{-2}yr^{-1}$, $\bar{z}$ is the lake's mean depth in meters, ρ is the replenishment coefficient or the fraction of the water volume lost annually through the outflow and R_{exp} is not lost via the outflow. It can be seen from this equation that a change

in phosphorus loading will result in a change in phosphorus concentration and, subsequently, in chlorophyll levels.

The Dillon and Rigler model implies direct proportionality between phosphorus loading and spring phosphorus concentrations. Summer phosphorus concentrations are related to previous spring concentrations. Thus, an assumption has been made that the relationship is valid for summer phosphorus concentrations also. This assumption is justified by data from Chapman and Terapchak (1976) who found spring and summer phosphorus data to be linearly related, the latter being approximately 87 percent of the former. Assuming a direct relationship between summer levels of chlorophyll and total phosphorus, changes in chlorophyll a concentrations may be predicted from changes in annual phosphorus loading rates since the loading change will result in a corresponding change in summer concentrations of total phosphorus in the lake.

For this purpose, a chlorophyll-phosphorus relationship was constructed for the study lakes. Since the lakes exhibited similar total nitrogen to total phosphorus ratios, the data from Long Lake and Lakes Johanna and Josephine were pooled in this analysis. The resulting relationship is plotted in Figure 43. Only data pairs from samples with TN:TP ratios greater than 12 were used in this analysis. The value 12 has been assumed to be the lower limit for proportionate uptake of phosphorus by phytoplankton. The equation for the prediction of summer average chlorophyll a concentration from the summer phosphorus concentration is:

$$(\text{Chl } a) = 0.541\ (P) - .006$$

From this model, a change in average summer chlorophyll can be predicted assuming that a change in total phosphorus loading results in a corresponding change in average summer phosphorus concentrations in lake water.

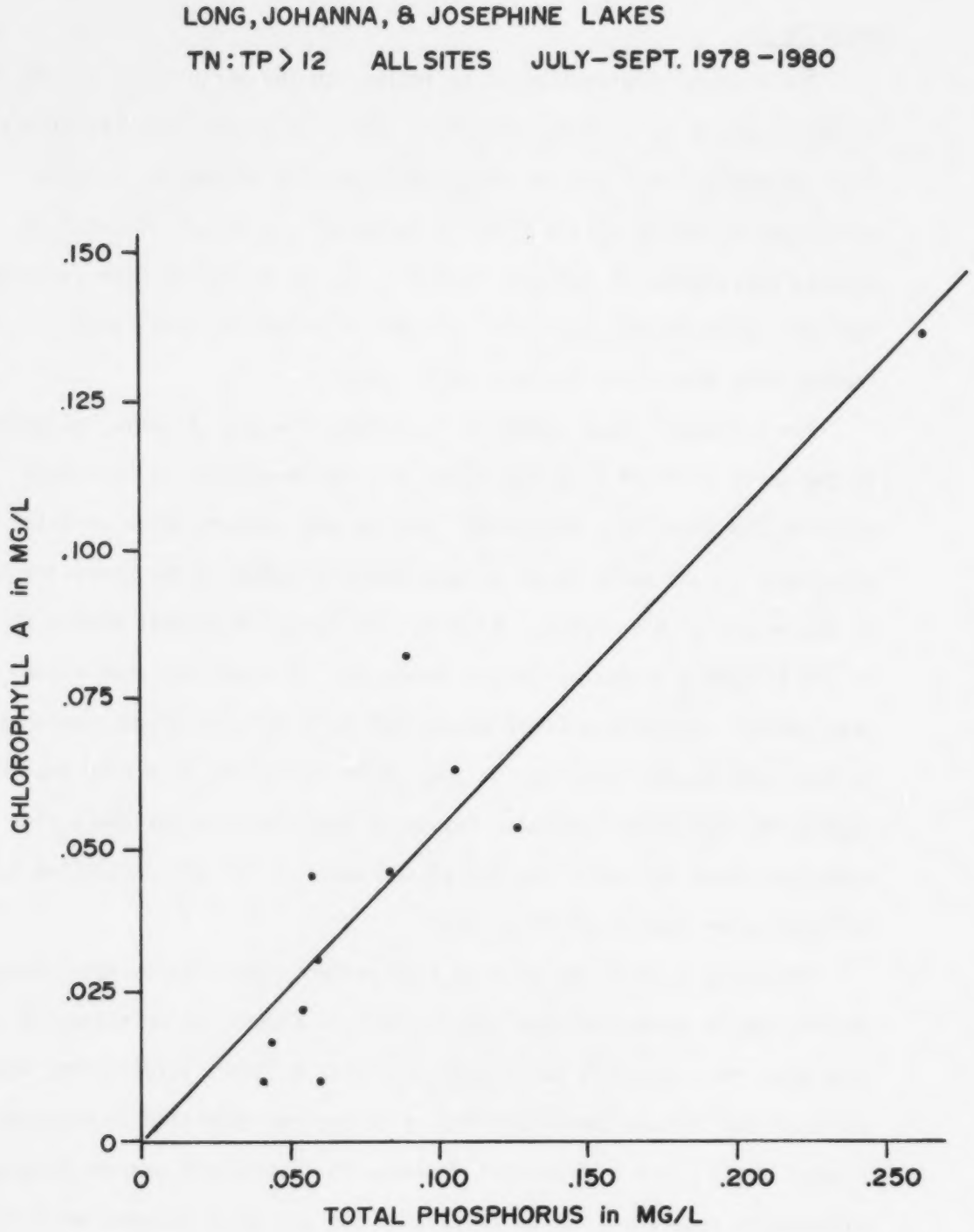


Figure 43. Chlorophyll/phosphorus relationship for Long Lake and Lakes Johanna and Josephine.

North Basin

The primary treatment given to inflows to the north basin of Long Lake is sedimentation of particulate matter from Rice Creek. The efficiency of such sedimentation is not yet documented, but the phosphorus loading reductions likely to result from sedimentation can be calculated from assumed percentages of sediment removal. Design engineers have estimated that the sedimentation basin will remove 15 percent of total phosphorus loading from Rice Creek (Hickok, pers. comm.).

The extremely short hydraulic residence time (ca. 12 days) of water in the north basin of Long Lake makes the concentrations of nutrients entering the basin very important. The in lake concentration of total phosphorus in the north basin is very closely linked to the concentrations in the waters of Rice Creek. A comparison of in-lake levels (Table 19) to the following tributary levels (Table 19), demonstrates that close association. Since Rice Creek enters and exits in the extreme north end of the north basin, there may be some short circuiting occurring that would impact the calculated hydraulic residence time, but the residence time is extremely short and water quality of the basin is largely controlled by influent water quality of Rice Creek.

The water quality response to a 15 percent reduction in total phosphorus loading can be predicted from the chlorophyll phosphorus relationship developed and previously described. Assuming a direct relationship between influent and in-lake concentrations, a 15 percent reduction in phosphorus loading would yield a 15 percent decrease in chlorophyll concentrations. Chlorophyll reductions may be calculated for any other assumed percentage change in total phosphorus loads. Summer chlorophyll a concentrations are calculated to decline from 0.086 mg/l to a level of 0.073 mg/l. This implies

Table 19. Summary of geometric mean summer water quality conditions for Long Lake tributaries. Annual averages were calculated over sampling dates during the July through September periods.

Year	Total P (mg/l)	Diss P (mg/l)	Ortho P (mg/l)	NO2 + NO3-N (mg/l)	NH3-N (mg/l)	TKN (mg/l)	TSS (mg/l)	VSS (mg/l)
RICE CREEK INLET								
1978	.361	.277	.192	.090	.198	1.66	14.4	5.4
1979	.143	.104	.056	.130	.088	1.53	5.9	1.9
1980	.592	.047	.006	.133	.750	5.33	56.2	35.0
RICE CREEK OUTLET								
1978	.246	.164	.123	.024	.091	2.67	10.7	4.7
1979	.127	.049	.009	.040	.038	1.62	11.3	7.7
1980	.348	.044	.003	.082	.378	4.32	29.6	22.2
PIKE LAKE OUTLET								
1978	.130	.050	.018	.006	.022	.89	18.7	8.0
1979	.132	.047	.004	.024	.029	1.49	19.0	10.5
1980	.186	.034	.004	.071	.065	1.54	23.1	12.1
JOHANNA DITCH INLET								
1978	.296	.175	.112	.059	.147	0.93	13.2	5.2
1979	.141	.063	.027	.240	.297	1.57	7.1	3.1
1980	.218	.042	.017	.283	.189	1.36	11.2	3.7

a corresponding improvement in Secchi disc transparencies from 1.68 meters to 1.84 meters in the north basin of Long Lake.

Such reductions are unlikely to be achieved, however, since the particulate fraction of the phosphorus load likely to be sedimented is not available for algal growth and would be sedimented in the lake if not removed in a sediment basin. The available fraction of the total phosphorus load will probably not be affected by the sedimentation process and thus no significant change in water quality is expected. Controls on phosphorus runoff from the Rice Creek watershed that will reduce the soluble phosphorus concentrations in Rice Creek are more likely to benefit water quality in the north basin of Long Lake. This situation involves the concept of bioavailability, a phenomenon that is presently being debated and is the subject of research.

Dredging in the north basin of Long Lake is merely cosmetic in nature. The removal of sediment deltas is not expected to have any beneficial water quality effect. Again, reduction in the soluble phosphorus load to Long Lake appears to be the most beneficial treatment that could be made.

South Basin

The principal lake restoration activity in the watershed of the south basin of Long Lake is the development of the marsh between Johanna and Long Lakes. As was pointed out previously in the Water Quality Section of this report, the water quality of the south basin of Long Lake seems to be buffered by the presence of the marsh, and its water quality does not vary significantly with changes in hydraulic loading. Nutrient loads from Johanna Ditch Inlet do not vary in response to variations in hydrology to the degree that Rice Creek inflow to the north basin does. Development of the marsh as a biological filter should increase its nutrient absorption. Design

engineers have estimated that the marsh will reduce total phosphorus loads by 40 percent (Hickok, pres. comm.). Short circuiting that now occurs in the marsh will be reduced, and the flow will be distributed over a larger area by distribution channels more effectively utilizing the marsh's absorptive capacity.

Other upland improvements designed to reduce stream-bank erosion and nutrient export from the watershed should reduce phosphorus loads to the lake. Coupled with development of the marsh filtration system, phosphorus loads will be reduced. It is not yet clear whether the effect of the marsh will be to reduce nutrient loads or to change the temporal movement of nutrients through the system. Most likely, a combination of the two effects will be observed. A reduction in nutrient loads will obviously benefit water quality. A change in the temporal movement of nutrients through the marsh will also improve water quality if its effect is to reduce loading during the active growing season and delay it until the growing season has passed. To the extent that the marsh acts as a sink for nutrients or as a retarding mechanism that delays nutrient loading, its further development should improve water quality in the south basin of Long Lake.

Treatment of the sediments of the south basin of Long Lake with calcium nitrate has been proposed to reduce internal loading. Presently, the external phosphorus load to the south basin is approximately 1000 kg annually. An additional load of 480 kg is calculated to come from the sediments of the lake. On an annual basis, internal phosphorus loading is about 31 percent of the total. It is a far greater portion (66 percent) of the load during the growing season. Calcium nitrate treatment is unlikely to eliminate internal loading entirely, and its potential effect on the reduction of phosphorus loading may not justify its cost.

All of the above comments regarding potential or expected water quality improvements are based on assumed reductions in phosphorus loads. It is also assumed that phosphorus is the limiting factor in the system. As this report points out, TN:TP ratios are often less than 12, indicating that phosphorus may not solely control productivity. Projected water quality improvements are provisional upon existence of suitable TN:TP ratios. Where phosphorus does not limit production, a reduction in phosphorus would result in higher TN:TP ratios. This action may shift the algal populations in the direction from bluegreen to green dominance. This shift may occur without a significant reduction in algal biomass, but would represent an improvement in water quality inasmuch as green algae are preferable to blue greens. Algal biomass could actually increase over existing levels if the TN:TP ratio was increased dramatically (as is a likely result of calcium nitrate treatment) to a point where phosphorus was solely limiting and to where the efficiency of phosphorus utilization approaches its maximum.

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